High sensitivity sensor for continuous direct measurement of bipolar charged aerosols

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Abstract - The disruptive generation of aerosols is known to cause particles to carry electrostatic charges. Anthropogenic aerosol may have a standard deviation of charges when generated that is different to other sources or equilibrated aerosols. A simple, low cost “Bipolar Charged Aerosol Sensor” (BCAS) has been developed to continuously measure charged aerosol in the ambient environment in real-time. Direct measurement of the current released from the charged aerosol particles when they deposit onto an electrode in a DC field is achieved using custom designed, sensitive electrometers. The mobility range of particles collected is defined by the DC field strength, air flow rate through the instrument and the electrode geometry. The mobility range of interest has been selected based on measurements made previously with a complex Laser Doppler Velocimetry (LDV) based instrument. The BCAS has been assessed in laboratory. The sensor design and initial measurement data will be discussed.

1. Introduction
Disruptively generated aerosol particles inherently carry some electrostatic charge. The magnitude of the charge mainly depends on the particle material, the method of generation, the conductivity of the atmosphere and the time for which the particles have been equilibrated with ions in the atmosphere. Charging mechanisms that cause a sudden increase in the charge distribution of atmospheric aerosols above that of the equilibrated Boltzmann distribution are: frictional charging of dry particles either due to high velocity airflows or disruptive spraying [1]; shearing of the electrical double-layer during liquid spraying [2]; corona charging from power lines [3] and charging due to atmospheric events, such as thunder storms [4]. However, most aerosols remain predominantly bipolar charged. This may be of a symmetric Gaussian type distribution or be skewed towards negative or positive depending on the material and generation method [5]). Therefore, separation of the polarities is required in order to directly measure a net charge of either polarity by the current they release on deposition.

Instruments to measure bipolar charged atmospheric aerosols in real-time are rare, with most available charged aerosol sensors being laboratory based. Some sensors require a pre-charging stage, so do not measure the natural charge on the aerosol, e. g. the Electrostatic Low Pressure Impactor (ELPI), a cascade impactor. Without the pre-charging stage activated it will measure only the net charge of an ambient aerosol, so an aerosol with a symmetrically distributed bipolar charge will register a net charge of zero [6]. Also, differential mobility analysers (DMA) can only measure one mobility and polarity of particles at a time and require a second step particle counter, making them complex [7, 8]. Phase Doppler Anemometry, the electrical single particle aerodynamic relaxation time
The bipolar charged aerosol sensor designed by Kulon et al. [13] is based on the same principle of operation as a Gerdien condenser [14] but with an increased bias voltage to collect lower mobility particles, rather than the more mobile ions. The sensor uses a number of deposition sites and senses particle deposition due to the electric field with a commercially available electrometer (Keithley 6517A). The amount of charge on the measured aerosol was between 0.5 and $5 \times 10^{-9}$ C. This level of charge is at least 4 orders of magnitude higher than that expected to be measured from aerosols released in the outdoor environment by common spraying techniques and detected some distance down-wind (Unpublished data measured with the PMA).

Previous measurements with the PMA enabled determination of mobilities of equilibrated environmental particles. Based on a comparison of these measurements with artificially generated aerosols, the level of charge was identified above which it is likely that disruptive spraying of aerosol has taken place. Airborne charged particles with mobilities above the range $\pm 8.3 \times 10^{-7}$ m$^2$V$^{-1}$s$^{-1}$ are likely to indicate an unusual event has occurred. A Bipolar Charged Aerosol Sensor (BCAS) has been developed to continuously monitor particles in this selected mobility range and give a real-time measurement of the current collected from the deposited particles. The aim was also to make the sensor relatively inexpensive and with a low power requirement so that battery powered operation was possible.

### 2. BCAS Design

The BCAS is based on an essentially Gerdien condenser design, where a bias voltage is applied to each of two identical concentric tube electrodes. This enables simultaneous bipolar operation if the bias voltages are set at different polarities, or measurement of different particle mobility ranges of one polarity. Charged particles of the mobility range of interest are selected by the bias voltage, air flow rate and the geometry of the sensor and deposit on the collection electrode giving up their charge. This can be measured as a current with a sensitive electrometer capable of determining a signal down to 10fA. The sensitive electrometers have been screened from noise associated with temperature, humidity, current leakage, microphone and external radio frequency noise whilst maintaining their high sensitivity. An ion filter is located on the front of each tube, which defines the upper mobility range that will reach the collecting electrode and will reduce the background noise from varying atmospheric ion concentrations. It is fabricated with the same dimension outer and bias tubes as the main collector, but is only 0.02m in length.

The sensor comprises a head unit and a base control unit connected by a 10 metre cable, enabling the head unit to be placed remotely. The head unit contains the measurement electrodes, bias voltage supplies and signal amplifiers and the base unit contains an LCD screen and enables selection of the operating parameters. Figure 1 shows the design of the main bias electrode. A dust filter extends over the outer tube. This consists of an acetal holder containing a filter mesh of 100μm diameter, made of stainless steel wire of diameter 15.4μm, resulting in an the overall blockage of only 25%. The fan (SUNON No: GB0545AFB1-8) is also fitted with a 100μm mesh stainless steel filter, although in this case it is to provide electrostatic screening.

A temperature and humidity probe is located between the measurement tubes in the head unit to enable continuous monitoring within the sensor during use. The sensor can be powered by external battery packs,
each capable of running the instrument for 20 hours. Data can be downloaded automatically to a PC through a serial interface and the sensor can store up to 36 hours of data on its internal stable memory.

2.1. Theoretical Aspects: Estimation of Collection Efficiency.

Consider a co-axial electrode system in which the bias tube radius is \( b \) and the collector rod radius is \( a \). If a voltage \( V \) is applied to the bias tube in this arrangement then the radial component of the electric field vector, \( E_r \) at a point distant \( r \) from the axis is defined below (1).

\[
E_r = -\frac{V}{r \ln \left( \frac{b}{a} \right)}
\]

\((b > r > a)\)

The fraction (\( \eta \)) of incoming ions/aerosols of mobility \( \mu \) (m\(^2\)V\(^{-1}\)s\(^{-1}\)), collected by an electrode system of length \( L \) (m) with a volume flow rate of \( \Psi \) (m\(^3\)s\(^{-1}\)) is defined in (2).

\[
\eta = \frac{2\pi \mu VL}{\Psi \ln \left( \frac{b}{a} \right)}
\]

The analysis may be extended to examine the overall collection efficiency (\( \eta_t \)) of the entire BCAS system first by calculating the collection efficiency (\( \eta_{SF} \)) of the small ion filter as a function of mobility. The fraction of ions/aerosols which are not removed by the small ion filter enter the main collector. Secondly, the collection efficiency (\( \eta_{MC} \)) of the main collector as a function of mobility is calculated. Therefore, we obtain,

\[
\eta_t = \eta_{MC} \left(1 - \eta_{SF}\right)
\]

hence

\[
\eta_t = \frac{2\pi V_{MC} L_{MC} \mu}{\Psi \ln \left( \frac{b}{a_{MC}} \right)} \left[1 - \frac{2\pi V_{SF} L_{SF} \mu}{\Psi \ln \left( \frac{b}{a_{SF}} \right)} \right]
\]

where \( V_{MC} \) is the bias voltage applied to the main collector (V), \( L_{MC} \) is the length of the main collector electrode (m), \( V_{SF} \) is the bias voltage applied to the small ion filter (V), \( L_{SF} \) is the length of the small ion filter electrode (m), \( a_{MC} \) is the diameter of the main collector electrode (m) and \( a_{SF} \) is the diameter of the small ion filter electrode (m).

In the above equation, the fixed numerical values appropriate to the BCAS are as follows:

\[\Psi = 4.8 \times 10^{-4} \text{m}^3\text{s}^{-1}\]

\[L_{SF} = 0.02m\]

\[L_{MC} = 0.10m, \ln \left( \frac{b}{a_{MC}} \right) = 0.910\]

\[\ln \left( \frac{b}{a_{SF}} \right) = 0.745\]
Here, the values of $V_{MC}$ and $V_{SF}$ are selectable between 0 and 850V. Figures 2 and 3 show the predicted behaviour of the collection efficiency as a function of the small ion filter bias with the main collector bias voltage as a parameter. The optimum performance for the mobility range of interest, which is centred on $10^{-6}$ m$^2$V$^{-1}$s$^{-1}$, should be obtained with both bias voltages set at around 600 V.

This analysis assumes that the flow within the BCAS is quasi-laminar. In practice this can only be approximately true, partly due to the presence of the electrodes along the flow path. These will inevitably shed some vorticity thus producing turbulence. Note however that the presence of the fine mesh dust filter on the inlet will tend to remove any transverse flow components from atmospheric turbulence entering the device.

3. Experimental Evaluation

The sensor was evaluated in the laboratory for background noise levels and signal to noise ratios for some aerosol releases. It was placed in a 0.21m$^3$ HEPA filtered chamber with a mixer fan. For the background measurements the sensor was operated in the undisturbed chamber for approximately 15 minutes. A reference airborne particle counter (APS TSI 3321) sampled air from the chamber to ensure particle counts in the 0.5 to 20µm size range remained low and stable. Results are shown in Table 1.

Aerosol measurements with the sensor were also conducted in the chamber described above. The chamber was cleared through a HEPA filter until the aerosol concentration was less than 2 particles per cm$^3$. An aerosol of 2% w/w sugar solution in distilled water was then added from a mini-nebuliser (Hudson RCI) activated with compressed air. The aerosol was left in the chamber for 1 minute and then the HEPA filter of the chamber was activated to clear down the concentration. Once the aerosol concentration reached the background level the next release was performed. Figure 4 show the raw current signal from the sensor for four sugar releases.

It was possible that the dust filter mesh on the inlet of the sensor could significantly alter the magnitude of current measured from aerosol releases, either by blocking particles from entering the sensor, or by discharging them if contact was made with the mesh. The procedure above was repeated using a suspension of 4µm diameter polystyrene latex spheres (Duke Scientific Inc.) with and without the grounded mesh in place to investigate any influence of the mesh on the measured signal.
4. Experimental results

| Ion filter bias | Main bias | Mesh ON/OFF | +ve channel Offset (pA) | +ve channel s.d. (pA) | -ve channel Offset (pA) | -ve channel s.d. (pA) |
|----------------|-----------|-------------|-------------------------|-----------------------|-------------------------|-----------------------|
| 0V             | 0V        | OFF         | 0.0026                  | 0.0009                | 0.023                   | 0.0016                |
| 0V             | 615V      | OFF         | 0.012                   | 0.0097                | 0.02                    | 0.0051                |
| 0V             | 615V      | ON          | 0.0146                  | 0.0049                | 0.0146                  | 0.0055                |
| 615V           | 615V      | OFF         | 0.0097                  | 0.0055                | 0.018                   | 0.0052                |
| 615V           | 615V      | ON          | 0.01                    | 0.0057                | 0.014                   | 0.0057                |

Table 1. Background noise level comparisons of sensor with various settings, the DC offset and standard deviation (s.d.) of the noise is shown (Average of approximately 10 minutes).

Figure 4. Four releases of 2% w/w sugar solution in distilled water from a mini-nebuliser, aerosol concentration less than 40 particles per cm$^3$ (615V bias voltage on both the ion filter and main electrode).

5. Discussion

By comparing the background noise measurements shown in Table 1, it can be determined that applying a main bias voltage of 615V changes the offset on the electrometer of the positive channel from 0.0026pA to 0.012pA. The negative channel offset is not significantly changed. This change on the positive channel could be due to a measured background level of ions, but as subsequent trials with the ion filter in operation did not significantly change the offset, it is most likely imposed by the presence of the DC voltage on the bias electrode, or originates from the activation of the supply voltage circuit. The standard deviation (s.d.) of each channel output increases with the application of a bias voltage on the main bias electrode. When there is neither a grounded mesh nor bias voltage on the small ion filter in front of the positive collection electrode, the positive channel noise is at its greatest (s.d. 0.0097pA). The application of either the grounded mesh or a bias voltage of 615V to the ion filter reduces this noise level to that of the negative channel. This indicates that noise from ions depositing on the positive electrode is removed by either method.

Figure 4 shows the raw data plot of four sugar releases recorded on the sensor. The releases were all generated by the same method and the peak concentration is below 40 particles per cm$^3$ for each release, although there is some variation in the amount generated purely imposed by the difficulty of repeatedly generating exactly the same amount of aerosol. The peaks can be clearly seen above the noise level of the sensor and they persist over a time period, making them distinct from any electronic noise spikes. The time period of the signal is very similar to the period of time which the APS measured particle counts above the background level. A noticeable feature of the signal is that there
appears to be a larger signal on the positive channel as compared to the negative channel, indicating a positive charge skew to the bipolar cloud. Further work will be completed to determine whether this is an instrument artefact or whether different materials can be measured with repeatable charge polarity skews. The effect of the aerosol generation method on this polarity skew will also be investigated.

The presence of the dust filter mesh reduced charge (normalised per particle) on both channels. This could be due to it preventing some particles entering the instrument or neutralising them by discharging them on contact. However, the charge polarity skew is maintained as the ratio between the two channels is not significantly different with or without the mesh in place (t test, P=0.46, n=3).

For operation in future outdoor trials it was decided to operate with the settings of 615V bias voltage for both the ion filter and main bias. This was to ensure no background ions would affect the signal as these were expected to be more variable over time in the outdoor environment. It was also decided to operate with the mesh in place as in outdoor conditions it is possible that large particles may be drawn into the sensor and cause it to require more regular cleaning.

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