Design and evaluation of a mini-Faraday cup for portable ultrafine particle sizer

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Abstract. In this study, a mini-Faraday cup for portable ultrafine particle sizer was designed, which consisted of a cylindrical metal case, a filter holder, a Teflon insulator, and an internal metal filter. In order to achieve high particle collection efficiency, a disc structure of metal filter was adopted in the proposed Faraday cup. Moreover, a high sensitive weak current amplifier was used and a spring probe electrode instead of the copper wire connecting between the Faraday cup and the weak current amplifier was used to eliminate the noise generated by vibration. The performance of Faraday cup electrometer was evaluated by a series of experiments. The results of the experiments showed that the current values of 220 nm charged particles for different number concentrations measured by the Faraday cup have good linear correlation, since the Adj. R-Square and the Pearson’s correlation coefficient are greater than 0.98 and 0.99, respectively. The experimental results of the prototype Faraday cup electrometer for particles ranging from 50 to 300 nm agreed well with the theoretical results. The comparative test between the self-developed aerosol electrometer and commercial electrometer were also presented. There was a good linear relationship between the current values measured by the two instruments. The self-developed mini-Faraday cup electrometer had advantages of high particle collection efficiency, small in size and light in weight, which was suitable for the portable measurements of atmosphere ultrafine particle.

1. Introduction
In recent years, many studies have shown that particles have a great impact on human health [1-3], therefore the detection of aerosol particles has become an important topic of air pollution monitoring and pollution source characterization [4]. The traditional method of particle measurement adopts aerodynamic flight time measurement method [5] or light scattering method [6]. In the process of atmospheric aerosol particles research at home and abroad, there are several commercial instruments which can be used to measure the size distribution and number concentration of particles. The instruments available include a Condensation Particle Counter (CPC) which uses particle condensation
growth and light scattering [7], an Electrical Low Pressure Impactor (ELPI) using inertia impaction of particles under low pressure [8], and an Optical Particle Counter (OPC) which uses light scattering characteristics of single-particle [9]. However, for small aerosol particles, especially those in submicrometer and nanometer size ranges, it is difficult to measure by the traditional optical method owing to weak light scattering from particles. It has been an effective method to measure the particle size distribution by using the electrical mobility of small aerosol particles [10]. Therefore, as an important module of the electrical mobility method, the Faraday cup electrometer, which can detect the charge on the particle, has been growing attention by people.

In recent years, the Faraday cup electrometer has been widely studied. Li et al designed a disc mini-aerosol Faraday cage, which had lower capacitance and lower pressure drop as compared with tube mini-aerosol Faraday cage [11]. Cao et al. designed a Faraday cup with simple structure, which can be used for larger sampling flow rate due to the low air resistance. However, the measurement range of the Faraday cup cannot meet the requirements of low particle concentrations [12]. Intra and Tippayawong designed a Faraday cup electrometer, which could detect the number concentration of aerosol particles from $10^{11}$ to $10^{14}$ #/m$^3$. Nevertheless, the number concentration of particles is generally less than $10^{11}$ #/m$^3$ in aerosol research [13]. Therefore, a Faraday cup with high particle collection efficiency and wide measurement range received more attention.

As an important index of portable ultrafine particle sizer performance, particle collection efficiency will affect the inversion concentration of ultrafine particles, and then affect the detection accuracy of ultrafine particles. Therefore, the high-performance Faraday cup has a great impact on the detection accuracy of the number concentration of ultrafine particles. In this paper, a new Faraday cup for measuring the charge of aerosol particles was designed. In order to achieve the high particle collection efficiency and wide measurement range, the following three strategies were adopted. First, a high sensitive weak current amplifier was used. Second, the disc structure was adopted to increase particle collection efficiency [11]. Finally, a spring probe electrode instead of the copper wire was used to connect the Faraday cup and the weak current amplifier module, since the spring probe electrode can eliminate the noise generated by vibration.

2. Design and experimental setup

2.1. Design of Faraday cup

![Figure 1. Schematic diagram of Faraday cup electrometer.](image1.png)

![Figure 2. Experimental setup for the performance evaluation of the Faraday cup.](image2.png)
According to the working principle of the Faraday cup [14], the schematic diagram of the Faraday cup with disc structure shown in Figure 1 was designed. The Faraday cup consists of a cylindrical metal case, a filter holder, a Teflon insulator, and an internal metal filter, which is electrically isolated from the metal case by Teflon stand. There are aerosol inlet and outlet ports on the top and side wall of the prototype, respectively, and an electrical interface at the bottom to export the weak electrical signals caused by charged particles, which are collected by the internal metal filter. A spring probe electrode instead of the copper wire is used to connect the Faraday cup and the weak current amplifier module, since the spring probe electrode can eliminate the noise generated by vibration. In order to minimize the interference of external electric noise to weak electrical signals in Faraday cup electrometer, the prototype was made of stainless steel material.

2.2. Experimental setup for Faraday cup

In order to evaluate the performance of the Faraday cup electrometer, a series of experiments were carried out using setup shown in Figure 2. The PSL particles in the diameters ranging from 50 to 300 nm were generated from a constant output atomizer. A mass flow meter was used to regulate the aerosol flow rate. The aerosol with PSL particles was transported to the diffusion dryer to remove water. Since the particles exiting from the constant output atomizer have been electrically charged, an aerosol neutralizer and an electrical precipitator were used at downstream of the diffusion dryer to obtain neutral particles. An adjustable DC high voltage power supply provided a stable high voltage for the discharge module of the charger. A commercial DC power supply was used to regulate the ion driving voltage of the unipolar charger. In the experiments, the neutral particles were delivered into the aerosol unipolar aerosol charger. And then the charged particles entered the CPC and Faraday cup equally by controlling the rate of aerosol intake of the two instruments. In order to maintain the same particles diffusion loss, the two gas paths were symmetrical. A commercial current amplifier was connected to the Faraday cup to amplify the weak electrical signals generated by charged particles. In this study, the signal current, \( I \), measured by the Faraday cup electrometer can be calculated by [15]

\[
I = ne(NQ_a)
\]

where \( n \) is the number of elementary charge units, \( e \) is the elementary unit of charge \((1.6 \times 10^{-19} \text{ C})\), \( N \) is the particle number concentration measured by CPC, and \( Q_a \) is the volumetric aerosol sampling flow rate into Faraday cup.

Figure 3. Particle size distribution of 220 nm particles in the experiment.

Figure 4. Particle collection efficiency of Faraday cup for 220nm particles at different concentrations and the comparison between Faraday cup electrometer and the reference data deduced from CPC.
3. Experimental results and analysis

Based on the experimental setup shown in Figure 2, the experiments were carried out to evaluate the particle collection efficiency of the designed Faraday cup aerosol electrometer. The monodisperse PSL particles in the diameter of 220 nm were selected as the test aerosol particles. The particle size distribution of 220 nm particles in the experiment is shown in Figure 3. As can be seen from Figure 3, particulate matter is mainly distributed around 220 nm with a peak concentration of 2400#/cm³. The particles generated from a constant output atomizer were charged by the independently developed unipolar charger whose performance has been assessed. By changing the flow rate, the number concentration of charged particles entering the two detectors was changed. The result of the experiments is shown in Figure 4.

As shown in Figure 4, the x-axis represents the value of \( NQ_\alpha \), where \( N \) is the particle number concentration measured by CPC, and \( Q_\alpha \) is the volumetric aerosol sampling flow rate into the Faraday cup. The y-axis represents the current value measured by the self-developed Faraday cup electrometer and the reference current deduced from the number concentration measured from CPC. The minimum output current measured by Faraday cup electrometer is 0.58 fA. Correspondingly, the number concentration of particles measured by CPC is 400#/cm³. A linear fit between the measured current value and the particle concentration has been performed. The Adj. R-Square and the Pearson’s correlation coefficient are greater than 0.98 and 0.99, respectively, confirming that there is an excellent fit and a good linear relationship between the measured current value and the particle concentration. The slope of the fitted line is \( 1.43 \times 10^{-19} \), which is close to the value of elementary charge. The result indicates that the self-developed Faraday cup electrometer has good counting performance. As a comparison, the reference value obtained from the particle number concentration calculation is also shown in the diagram. It can be clearly seen from Figure 4 that the experimental data agreed well with the theoretically predicted values.

According to the experimental setup shown in Figure 2, a new experiment on particle collection efficiency of Faraday cup electrometer was presented in this paper. The PSL particles in the diameters ranging from 50 to 300 nm were added to the atomizer to produce monodisperse aerosol particles. The aerosol flow rate was fixed at 0.3 LPM.

![Figure 5](image_url). Particle collection efficiency of Faraday cup for particles in the size range from 50 to 300 nm and the comparison between Faraday cup electrometer and the reference data deduced from CPC.

![Figure 6](image_url). The measured currents of the Faraday cup electrometer and the commercial electrometer at different number concentrations of 220 nm particles.
The result of the experiment was presented in Figure 5. As shown, the current value measured by Faraday cup electrometer for particles in the size range from 50 to 300 nm has good linear correlation. And the Adj. R-Square and the Pearson’s correlation coefficient are both greater than 0.98, the slope of the fitted line is $1.15 \times 10^{-19}$, which is closed to the value of elementary charge, too. As shown, the error between the measured current value and the calculated current in small size particle is greater than that in big size particle. This may be due to the unavoidable loss of diffusion in the tube and the fact that the smaller the particle size, the larger the diffusion loss.

4. Discussions

In order to visually display the performance of the Faraday cup electrometer, a comparative experiment was carried out between the module and a commercial aerosol electrometer. Figure 6 shows the measured currents of the Faraday cup electrometer and the commercial electrometer at different number concentrations of 220 nanometer particles, when they are used to simultaneously sample charged particles. It is evident in Figure 6 that the measured currents of two electrometers increase with the increase of the concentration of charged particles. Furthermore, the linear fitting operation of scatter points has been done. The currents measured by Faraday cup electrometer linearly increases with the increase of the values from the commercial electrometer, as shown in Figure 6. The slope is 1.03, indicating a good performance of the Faraday cup electrometer. We can see that the current measured by the self-developed Faraday cup electrometer is slightly smaller than that measured by the commercial electrometer, which may be due to the larger loss of particles in the detection module. Reducing the loss of particles will be the direction to improve the performance of the Faraday cup electrometer in the future.

5. Conclusions

In this study, a Faraday cup electrometer with high particle collection efficiency has been designed. The Faraday cup consists of a cylindrical metal case, a filter holder, a Teflon insulator, and an internal metal filter. And the metal filter is electrically isolated from the metal case by Teflon stand. A spring probe electrode is used instead of a copper wire to eliminate caused by mechanical vibration. In order to minimize the interference of external electric noise to weak electrical signals in Faraday cup electrometer, the prototype was made of stainless steel material.

The performance of the Faraday cup electrometer has been evaluated by various experiments in this paper. The experiments show that the current values of 220 nm charged particles of different number concentrations measured by the Faraday cup have good linear correlation. The Adj. R-Square and the Pearson’s correlation coefficient are greater than 0.98 and 0.99, respectively. The slope of the fitted line is $1.43 \times 10^{-19}$, and it is closed to the value of elementary charge. The experimental data agreed well with the theoretically predicted values. The experimental results of the prototype Faraday cup electrometer for particles in the size ranging from 50 to 300 nm are basically consistent with the theoretical results, too. It should be noted that the error between the measured current value and the calculated current in small particle size is greater than that in big particle size. This may be due to the unavoidable loss of diffusion in the tube and the fact that the smaller the particle size, the larger the diffusion loss. The experiments of the Faraday cup electrometer and commercial electrometer comparative test are also presented in the paper. There is a good linear relationship between two sets of data. And the slope is 1.03, indicating a good performance of the Faraday cup electrometer.

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