

An Aerosol Number Concentration Primary Standard

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This paper presents a method traceable to fundamental natural constants and the U.S. Army Primary Standards Laboratory's flow, voltage, and resistance standards to calibrate a condensation particle counter (CPC) by comparison to a primary standard aerosol electrometer (AE). The AE calculates aerosol concentration by measuring the electronic current and volumetric flow rate of a submicrometer calibration aerosol. This measurement is then compared to the CPC's optical measurement. An experimentally measured charge correction factor is used to correlate the two different measurement methods. The calibration aerosol is produced by atomizing an oil-alcohol solution with a constant output atomizer, imparting a known charge distribution on the aerosol with an aerosol neutralizer, and sizing to about 80nm ($\text{nm} = 10^{-9}\text{m}$) diameter with an electrostatic classifier. A traceable dilution system is used to calibrate the CPC at lower concentrations.

1. System Overview

The system compares an optical particle counter to an electronic particle counter. The generation of the calibration aerosol by electrostatic classification produces an aerosol containing multiple charged particles, creating a bias in the calibration. Therefore, to correlate the two measurements, the average charge on the aerosol must be known. By measuring the particle size distribution of the calibration aerosol, which has a known charge distribution as a function of particle size, a correction factor equal to the average charge on the aerosol can be applied to the CPC. This converts the physical number concentration of the CPC to a charge concentration, which is then verified by the standard. The overall calibration system contains three subsystems: the aerosol measurement, aerosol generation, and aerosol mobility spectrometer subsystems. Each is described below.

2. Aerosol Measurement Subsystem

2.1. Aerosol Electrometer

The aerosol electrometer used is a Standard Imaging MAX 4000 electrometer fitted with an aerosol adapter from a TSI 3068A electrometer. The primary standard AE calculates aerosol concentration electronically by measuring the number of charges per volume of the airflow. It performs traceable measurements of electronic current in the range of 500 fA to 100 fA ($\text{fA} = 10^{-15}\text{Amps}$) and volumetric flow rate in the range of $166.67\text{cm}^3/\text{s}$ (10Lpm). Charged particles in the aerosol flow are collected onto an absolute filter, which transfers the charge to the electrometer shown in figure 1. A Faraday cage is used to improve the signal to noise ratio of the electrometer.

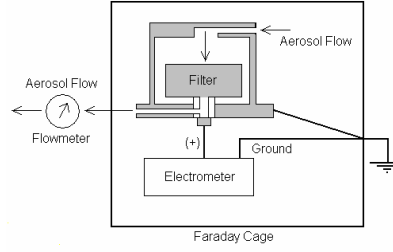


Figure 1: Aerosol electrometer schematic.

Assuming a single charge per particle, the aerosol charge and number concentrations are equivalent, expressed as

$$C_{AE} = \frac{q}{e} \cdot \frac{1}{tQ_{AE}} = \frac{I}{eQ_{AE}} \quad \text{Eq 1}$$

where C_{AE} is the aerosol number (charge) concentration in $1/\text{cm}^3$, q is the charge in Coulombs, e is the elementary unit of electronic charge in Coulombs, t is the sample time in seconds, Q_{AE} is the aerosol flow rate in cm^3/s , and I is the electronic current in Amps. The electrometer is calibrated before use with a standard electronic current generated by applying a voltage across a resistor, both traceable to the APSL.

2.2. Condensation Particle Counter

The CPC used is a TSI model 3010. It operates over a range of 0 to 10,000 particles/ cm^3 at a volumetric flow rate of $16.67\text{cm}^3/\text{s}$ (1 Lpm). The CPC initially condenses butanol onto the particles, amplifying their diameter to a size easily detected with conventional optics. The particles are then focused into a narrow stream with a nozzle and passed through a laser one by one. A photo detector collects the light scattered by each particle, creating a voltage pulse for each particle, as shown in figure 2. See reference [1] for a detailed description of the 3010.

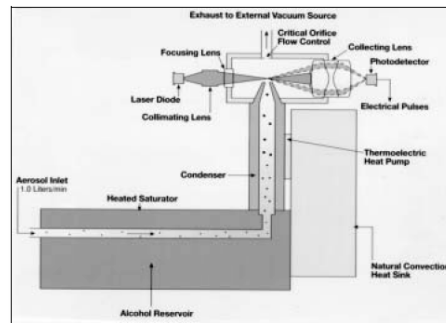


Figure 2: Schematic of TSI 3010 CPC as shown in reference [1].

The CPC functions by counting the number of voltage pulses during a time interval and measuring the aerosol volumetric flow rate. The number concentration is then

$$C_i = \frac{N}{tQ_{CPC}} \quad \text{Eq 2}$$

where C_i is the indicated aerosol number concentration in particles per cubic centimeter, N is the number of voltage pulses (particles), t is the sample time in seconds, and Q_{CPC} is the volumetric flow rate of the aerosol in cm^3/s . At higher concentrations, a coincidence correction is required to account for more than one particle residing in the viewing volume at once, shown below:

$$C_a = C_i \exp(C_i Q_{CPC} \tau)$$

Where C_a is the actual aerosol number concentration, C_i is the indicated aerosol number concentration calculated with equation 2, and τ is the effective time each particle resides in the viewing volume (see reference [1]). The C_a in the exponent can be approximated by C_i , yielding

$$C_a = \frac{N}{tQ_{CPC}} \exp\left(N \frac{\tau}{t}\right) \quad \text{Eq 3}$$

This is the actual number concentration of particles in the aerosol measured by the CPC.

3. Aerosol Generation Subsystem

The generation of a stable aerosol with a known charge distribution is requisite for the calibration of a condensation particle counter with an aerosol electrometer. The calibration aerosol is generated by atomizing an oil-alcohol solution with a collision atomizer to create a polydisperse aerosol, imparting a known charge distribution onto the aerosol particles with an aerosol neutralizer, and reducing the polydisperse aerosol into an approximately monodisperse calibration aerosol through electrostatic classification.

3.1. Atomization

A TSI 3076 constant output atomizer in re-circulating mode is used to create a stable, submicrometer, polydisperse aerosol from a solution of approximately 1cm^3 emery oil in 1000cm^3 isopropanol alcohol. The atomizer requires 241kPa (35psi) dry, filtered, compressed air at its input and must exhaust into atmospheric pressure. This method of atomization is trivial, just mix the solution and apply the compressed air. No ultra pure gas is required.

3.2. Aerosol Neutralization

The TSI 3077 aerosol neutralizer is used to impart a known and repeatable equilibrium charge distribution upon the aerosol. The neutralizer consists of a metal cylindrical housing containing a Krypton-85 radioactive source enclosed in a capsule, as seen in figure 3 below:

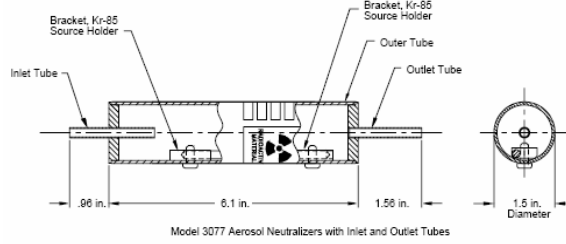


Figure 3: Aerosol neutralizer schematic, TSI 3077 manual.

The Kr-85 source creates an ionized atmosphere inside the neutralizer. This neutralizes most of the aerosol particles, with a fraction of the aerosol containing positive and negative charges. The fraction of particles with n charges is a function of particle diameter, with larger particles carrying more charges. An impactor is therefore installed prior to neutralization to remove larger particles from the aerosol. Neutralization is required in order to charge a known fraction of the aerosol particles so that a certain size particle can be filtered out of the polydisperse aerosol through electrostatic classification.

3.3. Electrostatic Classifier

The TSI 3080 Electrostatic Classifier with 3081 Long Differential Mobility Analyzer (DMA) measures the electronic mobility of aerosol particles, that is, the ability of a charged particle to move through an electric field when opposed by aerodynamic drag. This measurement is used here to size particles to 80nm ($\text{nm} = 10^{-9}\text{m}$), the diameter designated to simulate most biological agents. Electrostatic classification is performed to generate an approximately monodisperse aerosol from a charged polydisperse aerosol.

The DMA selects particles of a certain diameter as a function of the average applied voltage \bar{V} , sheath flow rate Q_{sh} , and number of charges on the particle n , as well as the DMA geometry and gas viscosity μ . The size particle selected is expressed as

$$\frac{Dp}{Cc(Dp)} = \left(\frac{1}{\mu} \cdot \frac{2e}{3} \cdot \frac{L}{\ln(r_2/r_1)} \right) \cdot \frac{\bar{V}}{Q_{sh}} \cdot n \quad \text{Eq 4}$$

Where Dp is the particle diameter and $Cc(Dp)$ is the Cunningham slip factor, which is a function of the gas mean free path and particle diameter. It is used as a correction to Stokes drag for transitional flow. L , r_1 , and r_2 define the geometry of the DMA, and e is the elementary electronic charge. For a constant temperature experiment, the terms in parenthesis are constant. Equation 4 allows the diameter of particle exiting the DMA in the monodisperse aerosol flow to be calculated based on measurements of sheath flow rate and voltage applied across the DMA for a particle with a given number of charges. Refer to the technical paper by Kinney and Pui [2] for the particle mobility theory of the DMA.

An important feature of equation 4 is that when setting the sheath flow rate and voltage to select a single charged particle ($n = 1$) with nominal effective diameter $Dp/Cc(Dp)$, particles with sizes that are integer multiples of the nominal effective diameter that contain multiple charges are also

selected. Specifically, for a nominal effective diameter $D_p/C_c(D_p)$ containing a single charge, particles with $2D_p/C_c(D_p)$ with $n = 2$ charges, $3D_p/C_c(D_p)$ with $n = 3$ charges, and so forth, are also part of the monodisperse calibration aerosol. This creates a bias between the AE and CPC.

3.4 Aerosol Generation Subsystem Schematic

A schematic of the system producing the calibration aerosol is shown below. The oil-alcohol solution is fed into the atomizer, generating a polydisperse oil aerosol. This is exhausted out of the atomizer into atmospheric pressure and drawn by a vacuum through the impactor, neutralizer, and DMA.

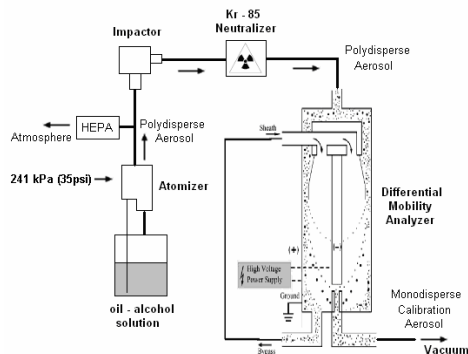


Figure 4: Schematic of aerosol generation system.

4. Aerosol Mobility Spectrometer Subsystem

This subsystem is used to measure the size distribution of the calibration aerosol, which has a known charge distribution as a function of particle diameter from aerosol neutralization. This measurement allows the calculation of the average charge on the aerosol, which is then used to eliminate the system bias. A second differential mobility analyzer (DMA) is used as a particle mobility spectrometer, from which a particle size distribution is calculated. The average charge is calculated in the form of the charge correction factor.

4.1. Charge Correction Factor

A charge correction factor is required to eliminate the system bias. Referring to equation 4, larger multiply charged particles along with single charged nominal size particles are present in the calibration aerosol, as shown below:

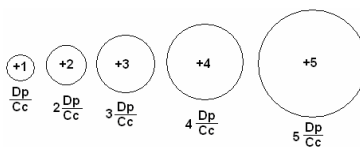


Figure 5: Constituents of calibration aerosol.

Considering figure 5, the AE measures 15 particles (charges), while the CPC measures 5 particles. A correction factor K of the following form is proposed to account for this bias:

$$C_{AE} = K \cdot C_{CPC} \quad \text{Eq 5}$$

Where C_{AE} is the standard concentration measured with the AE and C_{CPC} is the unit under test concentration measured with the CPC, both in units of $1/\text{cm}^3$. The calibration compares the standard charge concentration of the AE to the charge corrected particle concentration of the CPC. The concentrations in equation 5 are then expressed as

$$\left[C_o \left(\frac{Dp}{Cc} \right) + 2 \cdot C_o \left(2 \cdot \frac{Dp}{Cc} \right) + 3 \cdot C_o \left(3 \cdot \frac{Dp}{Cc} \right) + \dots \right] = K \cdot \left[C_o \left(\frac{Dp}{Cc} \right) + C_o \left(2 \cdot \frac{Dp}{Cc} \right) + C_o \left(3 \cdot \frac{Dp}{Cc} \right) + \dots \right]$$

$$K = \frac{\sum_{i=1}^{\infty} i \cdot C_o \left(i \cdot \frac{Dp}{Cc} \right)}{\sum_{i=1}^{\infty} C_o \left(i \cdot \frac{Dp}{Cc} \right)} \quad \text{Eq 6}$$

Where $C_o(iDp/Cc)$ is the concentration of particles with size iDp/Cc in the calibration aerosol. The concentrations in the summations are measured optically with the CPC. To compute K , the size distribution of the calibration aerosol must be measured.

4.2. Measurement of Calibration Aerosol Size Distribution

A second DMA is used as an aerosol electronic mobility spectrometer, from which the calibration aerosol size distribution can be computed. By holding the sheath flow rate constant and varying the voltage from 0 to 10,000 volts, a range of particle mobilities will exit in the monodisperse aerosol flow of the second DMA. At each voltage step, the CPC measures the particle concentration. This is repeated over a suitable number of voltage increments to create the mobility spectrum and in turn the size spectrum.

By inserting a second neutralizer and DMA at the outlet of the aerosol generation subsystem of figure 4, the mobility distribution of the calibration aerosol can be measured. A simplified schematic is shown below in figure 6.

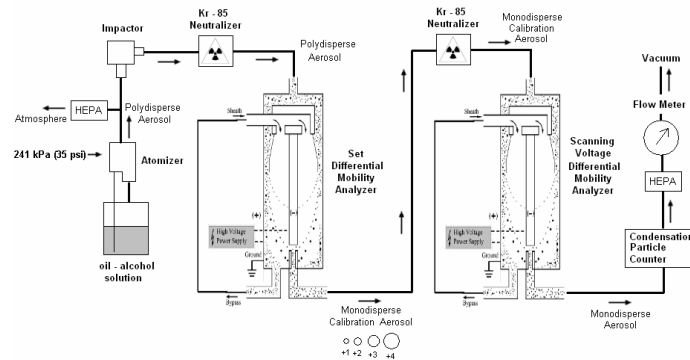


Figure 6: Simplified schematic of calibration aerosol size distribution measurement system.

The set DMA of the aerosol generation subsystem produces an aerosol of approximately constant size distribution. Over time, the size distribution will change due to evaporation of the alcohol in the atomization solution. This is accounted for by measuring a mobility spectrum at the beginning and end of the calibration. The scanning voltage DMA and CPC produce a mobility distribution of the calibration aerosol, with a representative scan shown below plotted as voltage versus concentration:

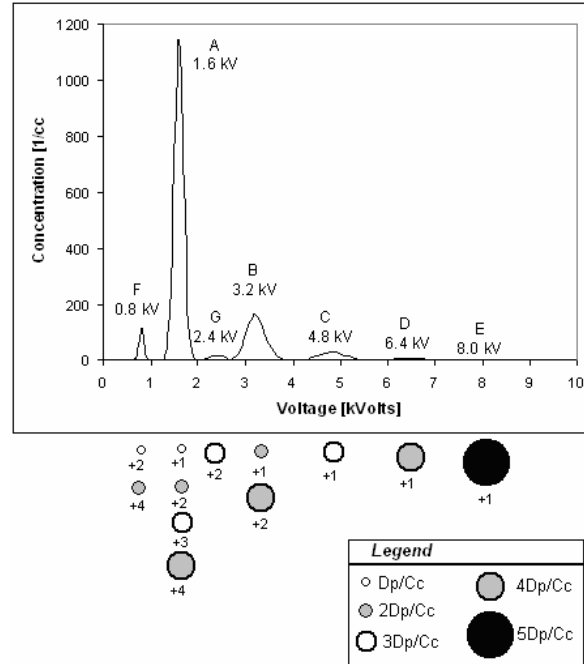


Figure 7: Calibration aerosol mobility spectrum, plotted as voltage versus concentration.

Peak A corresponds to the voltage set on the first DMA, all other parameters being equal. The voltages for the other peaks composed of mainly single charge particles (peaks B, C, D, E) are integer multiples of the voltage at peak A, according to equation 4. Figure 7 shows that the majority of particles present in the calibration aerosol are nominal diameter, single charged particles, as shown by peak A.

From experiment, the peak at 9600 volts corresponding to $6Dp/Cc$ has a negligible concentration. The sums in equation 6 are then truncated after $i = 5$, shown below:

$$K = \frac{\sum_{i=1}^5 i \cdot C_o \left(i \cdot \frac{Dp}{Cc} \right)}{\sum_{i=1}^5 C_o \left(i \cdot \frac{Dp}{Cc} \right)} \quad \text{Eq 7}$$

It is now left to determine the concentrations before neutralization, C_o , for each particle size in the above equation. These concentrations are then plugged into equation 7 to calculate the charge correction factor. Simplifying the analysis is the fact that no significant percentage of the aerosol particles carries a charge greater than +4. See reference [3] for a table of charging fractions. Neutralization results in, for a certain particle diameter Dp , a fraction of $C_o(Dp/Cc)$ containing a

certain number of charges n expressed as $f(Dp, n)$. Figure 7 shows that some peaks have only one particle size present, here designated as “pure” peaks, while other “compound” peaks are composed of more than one particle size. Consider the “pure” peaks C, D, and E. The measured concentration at peak C is

$$C_{C,measured} = C_o \left(3 \frac{Dp}{Cc} \right) \cdot f \left(3 \frac{Dp}{Cc}, +1 \right)$$

$$C_o \left(3 \frac{Dp}{Cc} \right) = \frac{C_{C,measured}}{f \left(3 \frac{Dp}{Cc}, +1 \right)}$$

That is, the measured concentration is equal to the fraction of particles with size $3Dp/Cc$ in the calibration aerosol containing a single positive charge after neutralization. The above equation is readily solved for $Co(3Dp/Cc)$ with experimental values of $C_{measured}$ and known values of $f(3Dp/Cc, +1)$. “Pure” peaks D and E can be solved similarly.

Now consider the “compound” peaks A, B, and F. Peak B is composed of two particle sizes and expressed as:

$$C_{B,measured} = C_o \left(2 \frac{Dp}{Cc} \right) \cdot f \left(2 \frac{Dp}{Cc}, +1 \right) + C_o \left(4 \frac{Dp}{Cc} \right) \cdot f \left(4 \frac{Dp}{Cc}, +2 \right)$$

$$C_o \left(2 \frac{Dp}{Cc} \right) = \left[C_{B,measured} - C_o \left(4 \frac{Dp}{Cc} \right) \cdot f \left(4 \frac{Dp}{Cc}, +2 \right) \right] / f \left(2 \frac{Dp}{Cc}, +1 \right)$$

Next, notice peaks A and F will both yield $Co(Dp/Cc)$. However, peak A has four terms while peak F has two terms. Peak F is therefore used to calculate $Co(Dp/Cc)$ to reduce the propagation of error. The solution using peak F is

$$C_{F,measured} = C_o \left(\frac{Dp}{Cc} \right) \cdot f \left(\frac{Dp}{Cc}, +2 \right) + C_o \left(2 \frac{Dp}{Cc} \right) \cdot f \left(2 \frac{Dp}{Cc}, +4 \right)$$

$$C_o \left(\frac{Dp}{Cc} \right) = \left[C_{F,measured} - C_o \left(2 \frac{Dp}{Cc} \right) \cdot f \left(2 \frac{Dp}{Cc}, +4 \right) \right] / f \left(\frac{Dp}{Cc}, +2 \right)$$

Each Co is then used to calculate K by equation 7.

5. Calibration System and Procedure

The calibration system consists of the calibration aerosol subsystem, with the vacuum provided by the aerosol measurement subsystem at a total flow rate of $183.33 \text{ cm}^3/\text{s}$ (11Lpm). Makeup air and a flow mixer are required to keep the monodisperse calibration aerosol flow under the $36.67 \text{ cm}^3/\text{s}$ (2.2Lpm) maximum aerosol flow rate through the DMA. The aerosol mobility spectrometer subsystem is inserted in series between the calibration aerosol subsystem and aerosol measurement subsystem when measurements of the charge correction factor are required. See figure 8 for a schematic of the calibration system.

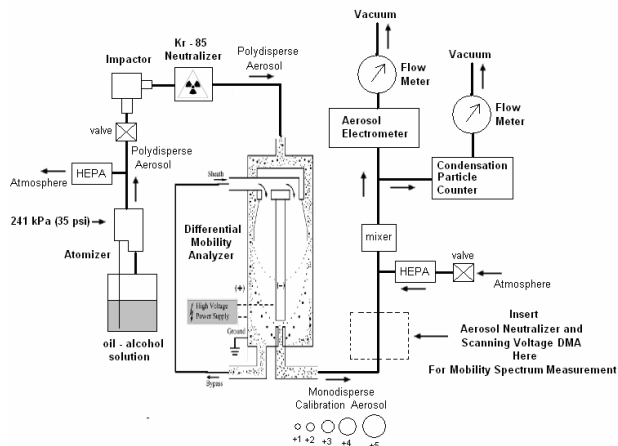


Figure 8: Calibration setup.

The calibration measures particle concentrations from approximately 10000 particles/cm³ to 4000 particles/cm³ indicated concentration by the CPC (equation 2). Initially a comparison is made at 10000 particles/cm³, after which the calibration aerosol size distribution is measured. Next a comparison between the AE and CPC is made at 8000, 6000, and 4000 particles/cm³, after which a second calibration aerosol size distribution is measured. Finally the comparison is made at 4000, 6000, 8000, and 10000 particles/cm³, concluding the calibration. The correction factor K used in data analysis is the average between the correction factors at 10000 particles/cm³ and 4000 particles/cm³.

6. Results

Charge corrected data for the CPC – AE comparison is shown on the left graph in figure 9. The data represents the charge concentration measured by the AE and the corresponding charge concentration measured by the CPC as KC_{CPC} . Raw data, uncorrected for charge, is shown as well to illustrate the bias present in the measurement. The right graph of figure 9 displays the particle corrected data. This data represents the physical number of particles/cm³ measured with the CPC (equation 3) and the corresponding number of particles/cm³ measured by the AE as C_{AE} / K . The bias has been removed, as shown below:

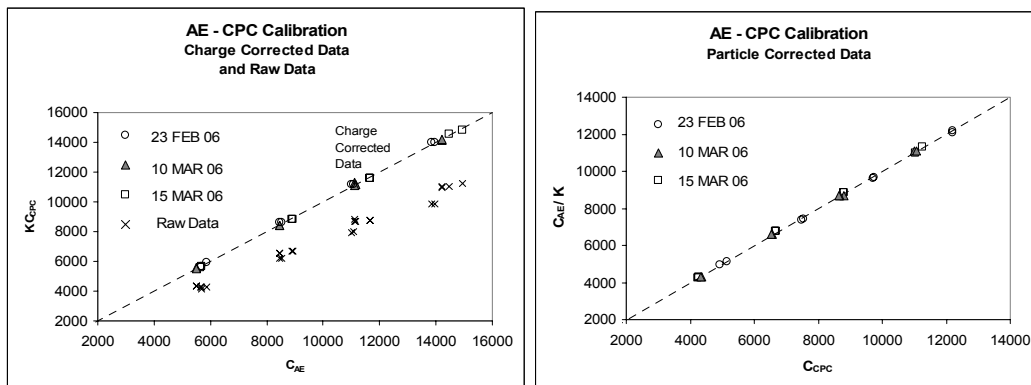


Figure 9: AE-CPC comparison data, charge and particle corrected, with raw data included to illustrate system bias.

7. Measuring Lower Concentrations – Dilution System

7.1. Dilution System

To calibrate at lower concentrations, a dilution system with flows traceable to the APSL is assembled. Using the CPC calibrated by the AE from 11000 to 4000 particles/cm³, a second CPC can be calibrated over the range of 11000 to 50 particles/cm³ using the dilution system. Below is a schematic of the dilution system:

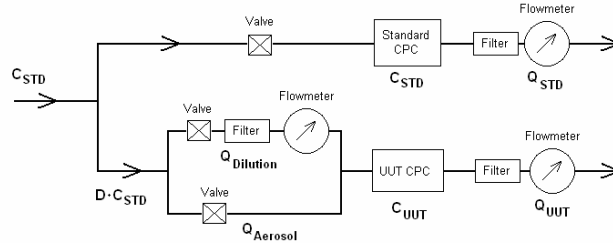


Figure 10: Dilution system schematic.

C_{STD} is the standard aerosol concentration, D is the dilution factor, C_{UUT} is the concentration measured by the unit under test (UUT) CPC, $Q_{Aerosol}$, $Q_{Dilution}$, Q_{UUT} , and Q_{STD} are all flow rates. The dilution factor D is defined as

$$D = \frac{Q_{Aerosol}}{Q_{UUT}} = \frac{Q_{UUT} - Q_{Dilution}}{Q_{UUT}} = 1 - \frac{Q_{Dilution}}{Q_{UUT}} \quad \text{Eq 8}$$

The UUT CPC measures aerosol concentration C_{UUT} while the standard CPC measures C_{STD} . The expression for equivalent concentrations is

$$D \cdot C_{STD} = C_{UUT} \quad \text{Eq 9}$$

which compares a standard, traceable concentration and dilution factor to the UUT CPC concentration.

The concentration of the standard CPC is kept constant at approximately 4300 particles/cm³ while the UUT CPC measures the concentration after a measured dilution down to 50 particles/cm³. A second dilution is then used with the CPC calibrated from 11000 to 50 particles/cm³ as the standard to calibrate a third CPC to 4 particles/cm³.

7.2 Dilution Calibration Results

The first stage dilution calibration results are shown in figure 11 below:

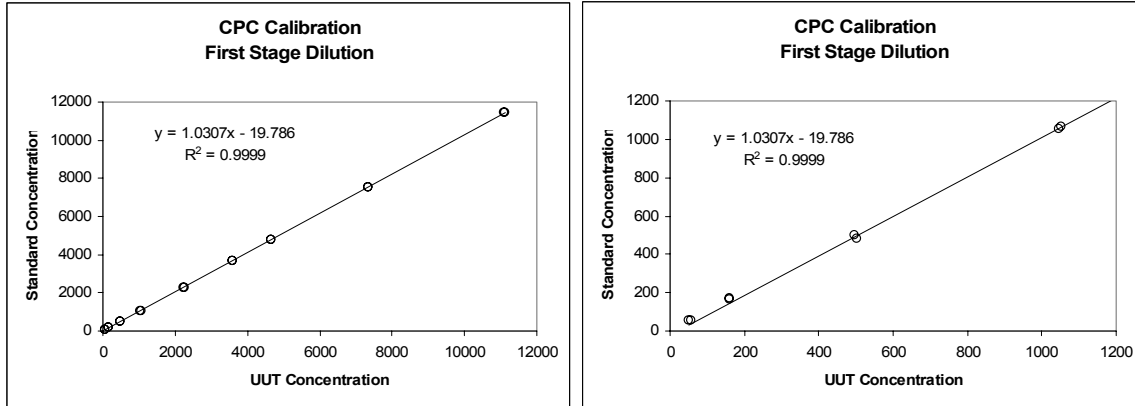


Figure 11: First Stage Dilution, 11000 – 50 particles/cm³.

The CPC in the first stage dilution is linear over more than two orders of magnitude. The results for the second stage dilution are shown next:

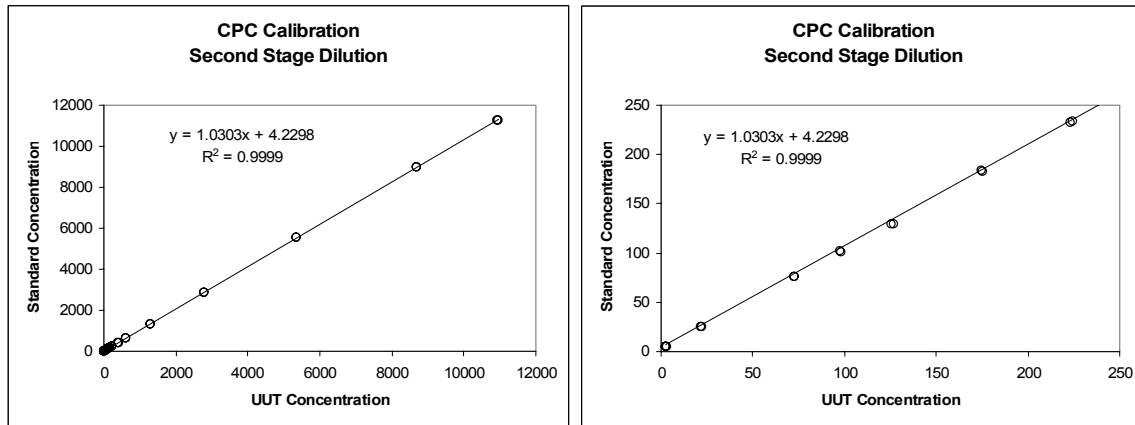


Figure 12: Second Stage Dilution, 11000 – 4 particles/cm³.

The CPC calibrated in the second stage dilution shows excellent linearity over about four orders of magnitude.

8. Measurement Uncertainties

8.1. Aerosol Electrometer Uncertainties

The AE has three sources of error: the electronic current, volumetric flow rate, and standard deviation about the mean of repeated concentration measurements. The time uncertainty is vanishingly small. The total uncertainty is expressed as

$$U_{C_{AE}} = \sqrt{\left(U_I \frac{\partial C_{AE}}{\partial I}\right)^2 + \left(U_{Q_{AE}} \frac{\partial C_{AE}}{\partial Q_{AE}}\right)^2 + U_A^2} \quad \text{Eq 10}$$

where C_{AE} is calculated from equation 1 and U_A is the standard deviation about the mean of repeated measurements.

8.2. Condensation Particle Counter Uncertainties

The CPC has three sources of error: the number of particles counted, volumetric flow rate, and standard deviation about the mean of repeated concentration measurements. The time uncertainty is vanishingly small. When counting N voltage pulses (particles), the counting error is

$$U_N = \frac{\sqrt{N}}{N}$$

The total uncertainty of repeated measurements by CPC is expressed as

$$U_{C_{CPC}} = \sqrt{\left(U_N \frac{\partial C_{CPC}}{\partial N}\right)^2 + \left(U_Q \frac{\partial C_{CPC}}{\partial Q}\right)^2 + U_A^2} \quad \text{Eq 11}$$

where C_{CPC} is calculated from equation 3 and U_A is the standard deviation about the mean of repeated measurements.

8.3. Charge Correction Factor Uncertainties

The charge correction factor K consists of five measurements of concentration Co by the CPC, each with uncertainties expressed using equation 11. These measurements are combined using equation 7, which is expanded below.

$$K = \frac{Co\left(\frac{Dp}{Cc}\right) + 2 \cdot Co\left(\frac{2Dp}{Cc}\right) + 3 \cdot Co\left(\frac{3Dp}{Cc}\right) + 4 \cdot Co\left(\frac{4Dp}{Cc}\right) + 5 \cdot Co\left(\frac{5Dp}{Cc}\right)}{Co\left(\frac{Dp}{Cc}\right) + Co\left(\frac{2Dp}{Cc}\right) + Co\left(\frac{3Dp}{Cc}\right) + Co\left(\frac{4Dp}{Cc}\right) + Co\left(\frac{5Dp}{Cc}\right)}$$

The uncertainty of K is shown below

$$U_K = \sqrt{\sum_1^5 \left[\left(U_{Co\left(\frac{iDp}{Cc}\right)} \right) \left(\frac{\partial K}{\partial Co\left(\frac{iDp}{Cc}\right)} \right) \right]^2} \quad \text{Eq 12}$$

8.4. CPC – AE Calibration Uncertainties

The measurement compares the charge measured by the AE to the charge corrected particle count of the CPC, as shown by equation 5. The total uncertainty of the unit under test charge corrected particle concentration is:

$$U_{C_{UUT}} = \sqrt{\left[U_K \frac{\partial}{\partial K} (KC_{CPC}) \right]^2 + \left[U_{C_{CPC}} \frac{\partial}{\partial C_{CPC}} (KC_{CPC}) \right]^2 + U_{C_{AE}}^2}$$

U_K is calculated from equation 12, $U_{C_{CPC}}$ from equation 11, and $U_{C_{AE}}$ from equation 10. This is the uncertainty reported for the condensation particle counter calibration.

8.5. Dilution System Uncertainties

The error in the dilution factor consists of the errors in the dilution and UUT CPC flow rates along with U_A , the standard deviation about the mean of repeated measurements of the dilution factor D.

$$U_D = \sqrt{\left[U_{Q_{dilution}} \frac{\partial D}{\partial K} \right]^2 + \left[U_{Q_{UUT}} \frac{\partial D}{\partial Q_{CPC_{UUT}}} \right]^2 + U_A^2}$$

The error in the standard CPC consists of the errors of equation 11 along with traceability error U_B .

$$U_{C_{STD}} = \sqrt{\left(U_N \frac{\partial C_{STD}}{\partial N} \right)^2 + \left(U_Q \frac{\partial C_{STD}}{\partial Q_{STD}} \right)^2 + U_A^2 + U_B^2}$$

The total uncertainty of the UUT CPC is a combination of the UUT measurement errors along with the errors of the dilution factor and standard CPC.

$$U_{C_{UUT}} = \sqrt{\left(U_{N_{UUT}} \frac{\partial C_{UUT}}{\partial N} \right)^2 + \left(U_{Q_{UUT}} \frac{\partial C_{UUT}}{\partial Q_{UUT}} \right)^2 + U_A^2 + \left(U_{C_{STD}} \frac{\partial (DC_{STD})}{\partial C_{STD}} \right)^2 + \left(U_D \frac{\partial (DC_{STD})}{\partial D} \right)^2}$$

Each dilution stage adds about 3% error to the CPC.

9. Conclusion

The method presented calibrates a condensation particle counter with a primary standard aerosol electrometer, traceable to APSL standards and fundamental natural constants. A CPC is then calibrated through a series of dilutions from approximately 11000 to 4 particles/cm³ with a series of dilutions, displaying excellent linearity. The overall uncertainty of the CPC calibrated over its entire range is 6% from 11000 to 7500 particles/cm³, 8% from 7500 to 4300 particles/cm³, 11% from 4300 to 50 particles/cm³, and 14% from 50 to 4 particles/cm³.

10. References

1. TSI Model 3010 Condensation Particle Counter Instruction Manual, Revision F, August 2002, pp. 1.2 – 1.3, 6.2, B.1 – B.2
2. P.D. Kinney, D.Y.H. Pui, G.W. Mulholland, and N.P. Bryer, Use of the Electrostatic Classification Method to Size 0.1 μm SRM Particles – A Feasibility Study, J. Res. Natl. Inst. Stand. Technol., vol. 96 number 2, pp. 147-176, March-April 1991.
3. TSI Series 3080 Electrostatic Classifier Instruction Manual, Revision F, March 2005, pp. B.9.