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DOE/SC-ARM-TR-146

Ultrafine Condensation Particle Counter Instrument Handbook

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August 2024

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How to cite this document:

Singh, A, and C Kuang. 2024. Ultrafine Condensation Particle Counter Instrument Handbook. U.S. Department of Energy, Atmospheric Radiation Measurement user facility, Richland, Washington. DOE/SC-ARM-TR-146.

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AC	alternating current
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
BNC	Bayonet Neill–Concelman
CCN	cloud condensation nuclei
CPC	modified ultrafine condensation particle counter
CPCuf	condensation particle counter
EPCAPE	Eastern Pacific Cloud Aerosol Precipitation Experiment
HEPA	high-efficiency particulate air
MAOS	mobile aerosol observing system
SMPS	scanning mobility particle sizer
UCPC	ultrafine condensation particle counter
UTC	coordinated universal time
VAC	volts of alternating current
W	Watts

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Model 3776 ultrafine condensation particle counter (pictured in Appendix A; more resources on manufacturer's website)

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4.0 Instrument Description

The Model 3776 ultrafine condensation particle counter (UCPC; pictured in Appendix A) is designed for researchers interested in airborne particles smaller than 20 nm. With sensitivity to particles down to 2.5 nm in diameter, this UCPC is ideally suited for atmospheric and climate research, particle formation and growth studies, combustion and engine exhaust research, and nanotechnology research.

Note: For some of the recent U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility deployments, the Model 3772/3750 has been modified by lowering its condenser temperature to 5 °C to operate as ultrafine particle counters. These modified CPCs are labeled as CPCuf. These modified ultrafine counters typically have a 50% particle detection limit of approximately 3 to 3.5 nm.

5.0 Measurements Taken

The primary measurement output from the UCPC is the particle number concentration, measured in units of #/cc. Accompanying recorded instrument outputs are the instrument error code, instrument temperatures (saturator, condenser, optics, and cabinet), instrument pressures (ambient, orifice, and nozzle), the laser current, working fluid liquid level, and sample aerosol flow rate.

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

Output data from the UCPC is recorded in column format with the following headers (and units), which are subject to revision: date (UTC, yyyy-mm-dd), time (UTC, hh:mm:ss), concentration (#/cc), instrument errors (hexadecimal code), saturator temperature[1], condenser temperature[1], optics temperature[1], cabinet temperature[1], ambient pressure[2], orifice pressure[2], nozzle pressure[2], laser current (mA), liquid level (full/not full), liquid level (fraction full), valve position (empty field), dilution flow set point (empty field), dilution flow measured (empty field), and aerosol flow rate (cc/min). Output data is recorded on the instrument computer at a time resolution of one second and written to text files spanning a time interval of one hour. The data columns describing the valve position, dilution flow set point, and dilution flow measured are empty fields, since no dilution system is installed for the Model 3776 UCPC.

Note: In recent years, dilution flow corrections have not been applied, and currently no ARM CPC uses any form of dilution correction.

6.2 Data Ordering

Data from the Model 3776 UCPC can be accessed and ordered through the ARM website. Data is organized by measurement location. The filename nomenclature generally adheres to this format: {sitename-aos-cpcu/cpcuf[3]-sitecode-a1/b1.yyyymmdd}. In this structure:

- Sitename: name of the specific campaign
- AOS: Aerosol Observing System
- CPCu/CPCuf: ultrafine-mode CPC; 50 % detection efficiency (D_{50}) of 2.5 nm (CPCu) and 3-3.5 nm (CPCuf)
- Site code: unique code for the station (for e.g., M1, C1, E13, S3 etc.)
- a1/b1: This notation refers to data processed at two levels that is accessible from the ARM website. At level a1, raw data is imported from the CPC serial datastream at one-second intervals. Notably, as concentration is the primary variable of interest, any errors detected by the CPC firmware and additional data quality flags (outlined in Section 6.4) are also marked. Moving to level b1, any further

[1] All temperatures in degrees Celsius.
[2] All pressures in kPa.
[3] Either CPCu or CPCuf will be available.

data quality flags, as determined by a mentor's review, are incorporated. Additionally, for CPCuf where flow correction is enabled, concentrations are adjusted for flow correction. We generally recommend users to use the b1 level.

6.3 Data Plots

A plot of representative Model 3776 UCPC data is presented in Figure 1. Particle number concentration measurements are presented as a function of sampling time for typical measurements obtained during the ARM Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE; (https://www.arm.gov/research/campaigns/amf2023epcape) on 4 February 2024.

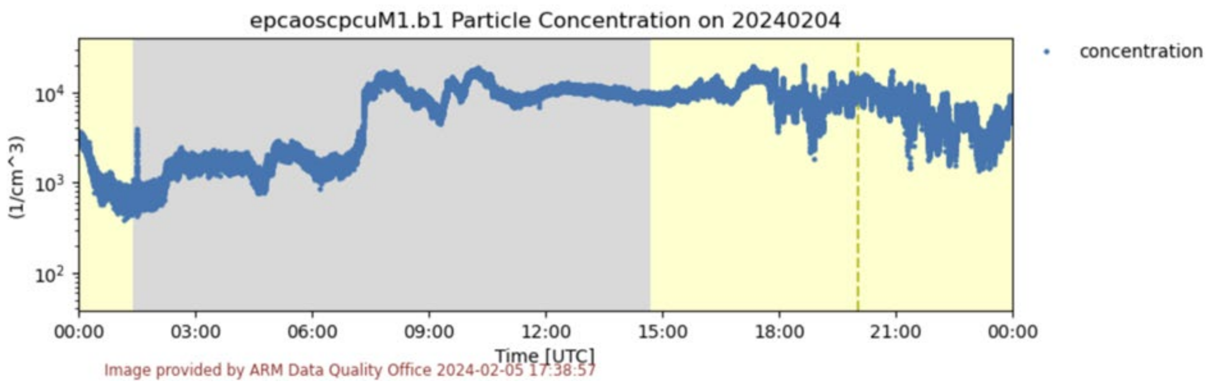

Figure 1. Data plot of aerosol number concentration, as measured by the mobile aerosol observing system (MAOS) Model 3776 UCPC deployed at Scripps Pier, La Jolla, San Diego, California during the EPCAPE campaign on 4 February, 2024. Plot was generated using the ARM Data Quality Diagnostic Plot Browser (https://dq.arm.gov/dq-explorer/#/metrics).

6.4 Data Quality

The first level of data quality evaluation consists of automated data flagging by the Data Quality Office, based on mentor-supplied evaluation criteria. Flags are generated whenever measured data (primary output and/or metadata such as instrument housekeeping) are above, below, or outside defined maximum threshold ranges. Examples of these threshold ranges are listed below; they are intended to be illustrative rather than definitive.

- Maximum nozzle pressure = 3-3.5 kPa (typically). The nozzle pressure measures pressure drop across the nozzle and indicates whether the nozzle is clogged by debris. Nozzle pressures in excess of 3-3.5 kPa will generate a warning.
- Minimum orifice pressure = 50 kPa (or 50 % of the ambient pressure). The orifice pressure measures the pressure drop across the critical orifice, which controls the inlet flow rate and thus indicates whether sufficient vacuum is being supplied to the instrument in order to yield 0.3 lpm flow. Orifice pressures below 50 kPa will generate an alarm.
- Nominal aerosol flow rate range = 48.0-52.0 cc/min. Operating outside this range could indicate a clog in the aerosol sample capillary, which could result in under-counting.

- Nominal saturator temperature range = 38.5 °C-39.5 °C. Operating outside this temperature range will result in a deviation from expected butanol vapor pressure and resulting particle size detection limit (nominally 2.5 nm in diameter). Saturator temperatures outside this range will generate an alarm.
- Nominal condenser temperature range = 9.5 °C-10.5 °C. Operating outside this temperature range will result in a deviation from the expected vapor saturation ratio and resulting particle size detection limit (nominally 2.5 nm in diameter). Condenser temperatures outside this range will generate an alarm.
- Nominal optics temperature range = 38.0 °C-42.0 °C. Operating outside this temperature range could lead to vapor condensation on the optics surface. Optics temperatures outside this range will generate an alarm.
- Minimum butanol level (fraction) = 0.5. Beneath this fill level, there may not be sufficient butanol vapor to reach the expected vapor saturation ratio and particle size detection limit (nominally 10 nm in diameter). Butanol levels below this limit will generate an alarm.
- Minimum laser current = 20 mA. Operating beneath this current value indicates declining laser health. Laser currents below this limit will generate an alarm.
- Cabinet temperature range =5-40 °C: Operating outside the temperature range of 5-40 °C for the cabinet indicates abnormal CPC operation. Such an operation may impact the CPC's ability to maintain stability in temperature across components like the condenser, saturator, and optics block. If the CPC operates outside this specified range, it triggers an alarm.
- The second level of data quality evaluation involves automatic generation of the following plots, in collaboration with the Data Quality Office. These automated plots include time series of various key instrument housekeeping variables, and comparison with other co-located particle counter or sizers such as fine CPC or CPCf, or a scanning mobility particle sizer (SMPS).

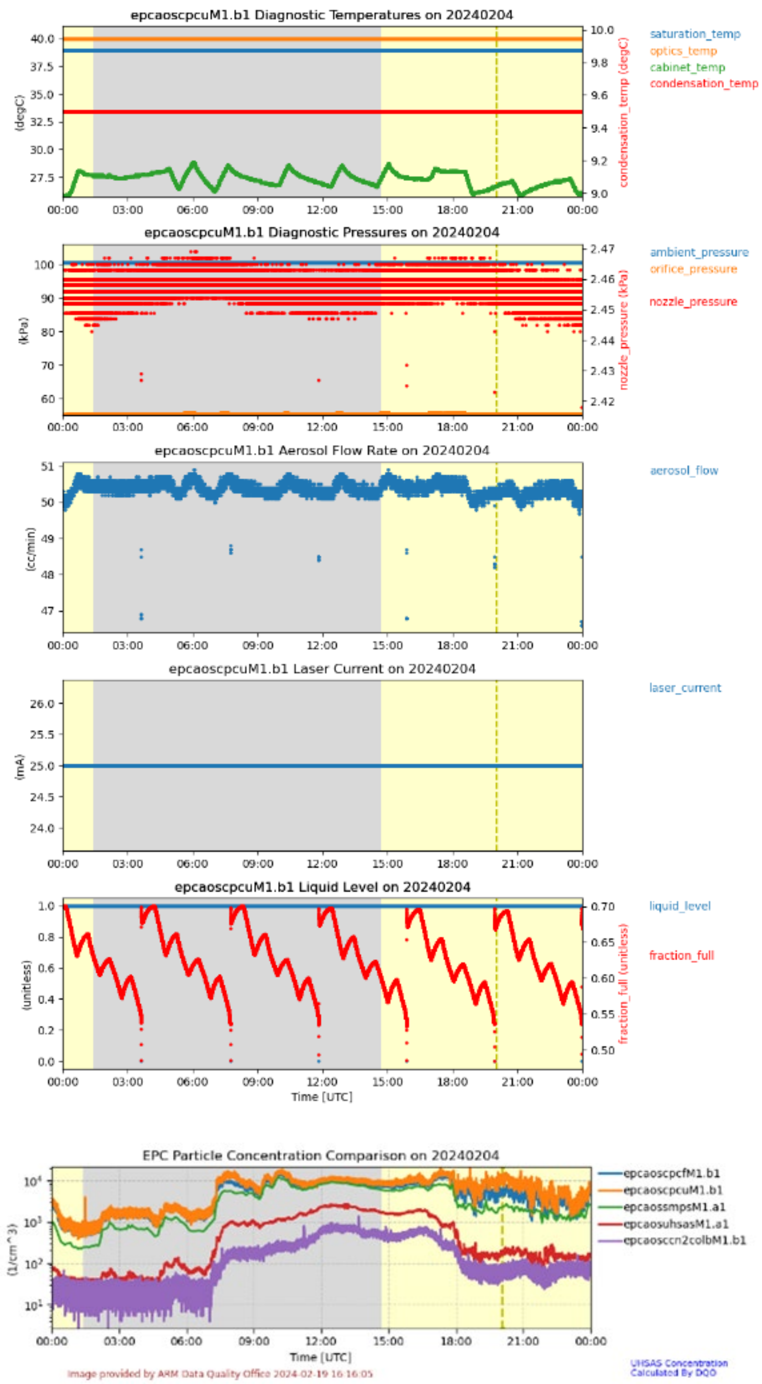

Figure 2. Automated data plot generated by the ARM Data Quality Diagnostic Plot Browser, illustrating CPCu data alongside comparisons with other co-located measurements from the MAOS. These observations were conducted at Scripps Pier in La Jolla, San Diego, California, during the EPCAPE campaign on 4 February, 2024.

Diagnostic plots as shown in Figure 2 serve the purpose of assessing the stability of CPC operation during continuous usage, helping to identify and isolate any issues with the instrument, and offering a sanity check of the measurements.

For example:

- Nozzle pressure as a function of time: a steady increase in nozzle pressure over time proves the nozzle is indeed clogged and requires cleaning. See the manufacturer's website for more instruction.
- Comparison of co-located Model 3772 and Model 3776 particle number concentration measurements as a function of time: the Model 3776 particle number concentration should always be equal to, or greater, than the Model 3772 particle number concentration, since the Model 3776 particle size detection limit is 2.5 nm and the Model 3772 particle size detection limit is 10 nm. Comparison of measurements from both CPCs provides a quick assessment of relative CPC performance. This comparison becomes particularly important for the scenario where the Model 3776 is under-counting with respect to the Model 3772.
- If both the CPCf and CPCu are situated within the same sample line, comparing the CPC time series with instruments in separate sample lines within the AOS can also reveal relative indications of data quality issues. For instance, comparing time series between the CPCf and CCN concentration at the highest supersaturation can provide valuable insights.

6.5 Calibration Database

The Model 3776 CPC is calibrated prior to instrument installation and deployment. Calibration activities include verifying inlet flow rate with a low-pressure-drop bubble flow meter and determining the size-dependent particle counting efficiency, according to methods defined in Hermann et al. (2007) and Mordas et al. (2008). In typical deployments, both CPCu and CPCf are used, and size-resolved bias characterization is carried out between CPCf and either CPCu or CPCuf. This assessment, conducted under laboratory conditions, serves as a baseline characterization to indirectly evaluate the CPC's performance during field operations. CPC calibration data is collected and maintained by the instrument mentor.

Note: In recent years, dilution flow corrections have not been applied, and currently, no ARM CPC uses any form of dilution correction.

7.0 Technical Specification

7.1 Units

The measured quantity of interest is the particle number concentration, measured in units of particles per cubic centimeter (#/cc).

7.2 Range

The range in particle number concentration is 0 to 3×10^5 #/cc. The UCPC operates in single-count mode with continuous, live-time coincidence correction between 0 and 3×10^5 #/cc. For concentrations between 3×10^5 and 1×10^6 #/cc, however, the high level of particle coincidence degrades the measurement accuracy, requiring further calibration against a high-concentration reference.

7.3 Accuracy

With the sample flow rate monitored online by a differential pressure transducer across the sample capillary, the particle concentration accuracy is strictly a function of statistical noise associated with single-particle counting and is, therefore, concentration-dependent. Using a typical sampling time of one second, a concentration measurement typical of very clean environments (~100 #/cc) has an accuracy of ±10%, while a concentration measurement typical of polluted environments (~5000 #/cc) has an accuracy of ±1.5%.

7.4 Repeatability

With the sample flow rate monitored by a differential pressure transducer across the sample capillary, the particle concentration repeatability is a function of statistical noise associated with single-particle counting and is, therefore, concentration-dependent. Using a typical sampling time of one second, successive concentration measurements typical of very clean environments (~100 #/cc) have a repeatability within ±10% of each other, while successive concentration measurements typical of polluted environments (~5000 #/cc) have a repeatability within ±1.5% of each other.

7.5 Sensitivity

Particle counting sensitivity, with respect to sampled aerosol measurements (concentration linearity), is accounted for in the signal-processing electronics. Particle concentrations are corrected for concentration-dependent counting coincidence, up to concentrations of 3×10^5 #/cc.

7.6 Uncertainty

Uncertainty in particle number concentration measurements is a function of the statistical error associated with the number of particle counts and the accuracy and repeatability of the aerosol sample capillary flow rate Q. The relative statistical counting error σ_r is calculated from the total count n, according to the equation:

$$\sigma_r = \frac{\sqrt{n}}{n} \quad (1)$$

The total uncertainty can then be calculated through uncertainty propagation within the equation for calculating particle number concentration:

$$concentration = \frac{n}{Q \cdot t} \quad (2)$$

Where t is the sampling time interval.

7.7 Output Values

Output data from the UCPC is recorded in column format with the following headers (and units): date (UTC, yyyy-mm-dd), time (UTC, hh:mm:ss), concentration (#/cc), instrument errors (hexadecimal code), saturator temperature (°C), condenser temperature (°C), optics temperature (°C), cabinet temperature (°C), ambient pressure (kPa), orifice pressure (kPa), nozzle pressure (kPa), laser current (mA), liquid level (full/not full), liquid level (fraction full), valve position (empty field), dilution flow set point (empty field), dilution flow measured (empty field), and aerosol flow rate (cc/min).

8.0 Instrument System Functional Diagram

The Model 3776 UPC consists of three major subsystems: the particle sensor, the signal-processing electronics, and the particle flow system. The particle sensor consists of a saturator, condenser, and optical detector, as shown schematically in Figure 3.

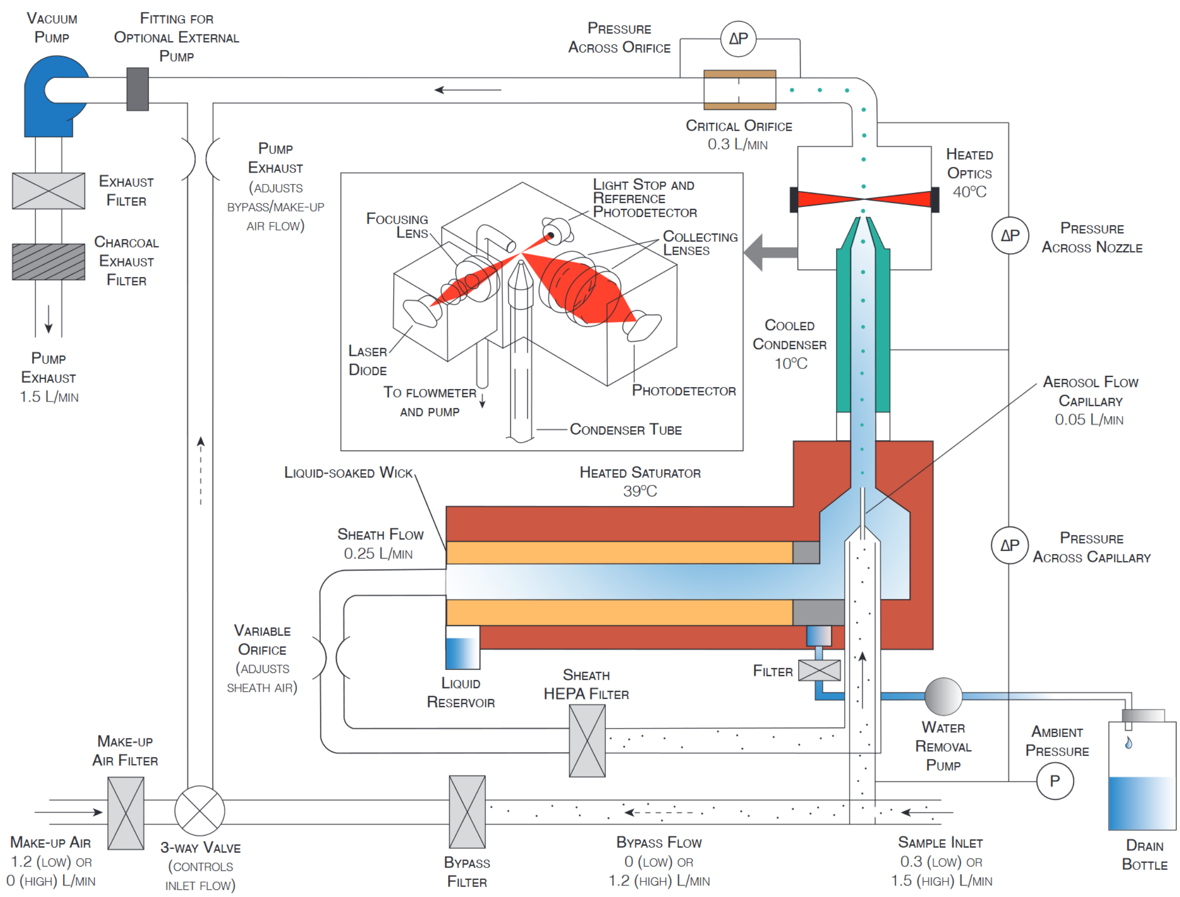

Figure 3. Flow schematic of the Model 3776 UCPC adapted from the manufacturer.

The sensor grows the sampled particles into larger droplets, which are detected optically. Laminar aerosol flow is sampled through the inlet and then split to form aerosol sample flow and sheath flow. The sheath flow is filtered before entering the saturator section, where butanol liquid, evaporated from a heated wick, saturates the sheath flow with butanol vapor. The aerosol sample flow passes through a capillary tube and is injected into the centerline of a vertical condenser tube before rejoining the vapor-saturated sheath air, as a laminar flow. The combined aerosol sample and butanol vapor-saturated sheath flow then enter the condenser, which is cooled with a thermo-electric device. There, butanol vapor becomes super-saturated and condenses onto the aerosol particles; thus forming larger droplets. The butanol droplets pass through a nozzle into the optical detector consisting of a laser diode, various focusing and collecting lenses and a photodiode detector. Butanol droplets that pass through the laser will scatter light, which is detected by the photodiode and converted into electrical pulses. These pulses are counted and, at high particle concentrations, corrected for particle coincidence.

9.0 Instrument/Measurement Theory

The UCPC essential feature is the growth of sampled particles through working fluid condensation, prior to optical counting. When vapor surrounding the particles reaches a certain degree of supersaturation, it begins to condense on the particles; a process called heterogeneous nucleation. If super-saturation levels are too high, however, vapor condensation can occur without sampled particles present: a process called homogeneous nucleation. In these circumstances, working fluid vapor molecules collide to form clusters. Particle counts from droplets generated through homogeneous nucleation result in instrument noise and should be avoided. Optimal UCPC performance is achieved by operating at a super-saturation level just below the homogeneous nucleation limit. The particle size detection limit is a strong function of the super-saturation ratio operating value and can be calculated from theoretical predictions relating particle diameter and vapor super-saturation ratio (Ahn and Liu 1990, Stolzenburg and McMurry 1991).

The UCPC design is noteworthy, compared to the CPC design, because using sheath air permits sampled aerosol to be confined to the condenser tube centerline, where super-saturation levels are the highest, thus resulting in high detection efficiency for the smallest particles. The sheath air flow-design also reduces response time and particle diffusion losses due to reduced sample path residence time. Further design details and theoretical models for the UCPC can be found in Stolzenburg and McMurry (1991).

10.0 Setup and Operation of Instrument

Setup steps:

1. Remove all protective caps from the inlet sample port and exit flow ports at the back the instrument, and remove covers from the BNC connectors.
2. Mount the bottle bracket on the back panel using the provided screws and washers. Connect the bottle tube fitting to the fill port at the back panel of the instrument.
3. The UCPC uses reagent-grade (>99.9 % purity) n-butyl alcohol (butanol) as the working fluid. Pour the butanol into the fill bottle until at least ½ full.
4. Plug the power cord into the receptacle on the back panel of the CPC and plug it into the AC power source. The instrument accepts input voltages in the range of 100-240 VAC, 50/60 Hz, 210 W maximum. Apply power to the UCPC by turning on the switch next to the power cord on the back panel. The instrument will begin a warm-up sequence that typically lasts ten minutes.

5. The air flow containing butanol vapor emits exhaust from this fitting, located at the back panel of the UCPC. The exhaust should be directed away from the work area using a piece of tubing connected to this port.
6. Place the UCPC on a level surface. Ensure the cooling fan on the back panel of the UCPC is exposed to ambient air. Connect the black sampling tubing to the UCPC inlet tube.

In its standard setup, the UCPC includes an internal pump to regulate flow. However, for field deployment, the UCPC undergoes modification to operate using an external vacuum source.

The Model 3776 UCPC operates nominally within the following environmental conditions and ranges:

- Altitude: Up to 2000 m (6500 ft)
- Inlet pressure: 75 to 105 kPa (0.74 to 1.05 atm)
- Operating temperature: 10 to 35 °C
- Ambient humidity: 0 to 90% relative humidity non-condensing

During ARM deployments, the 3776 UCPC samples within an environmentally controlled measurement container, in accordance with the manufacturer's environmental requirements.

11.0 Software

Data acquisition and instrument control is accomplished through a LabView-based program, written at Brookhaven National Laboratory. The data is parsed and saved in hour-long text files on the instrument computer. Instrument firmware commands are available for the UCPC and are listed in the manufacturer's manual.

12.0 Calibration

The Model 3776 UCPC undergoes calibration prior to installation to characterize the inlet flow rate and size-dependent particle counting efficiency. The inlet flow rate is measured with a low-pressure-drop bubble flow meter, which nominally yields an inlet flow rate of 0.3 ± 0.015 lpm (low flow mode) or 1.5 ± 0.05 lpm (high flow mode). The aerosol sample flow uses a factory calibration relating capillary pressure drop to capillary flow rate; with a nominal flow rate of 0.05 ± 0.005 lpm.

The 3776 UCPC has a nominal D_{50} of 2.5 nm, where D_{50} is defined as the particle diameter at which 50% of sampled particles are detected. Counting efficiency is a function of particle diameter and to some extent particle composition; determined using the calibration protocol described in Hermann et al. (2007). Calibration aerosol is generated in a tube furnace via the evaporation-condensation method, and size classified with a TSI Model 3080/82 electrostatic classifier and Model 3085 nano differential mobility analyzer. Counting efficiency is calculated by comparing UCPC readings to a TSI Model 3068B aerosol electrometer. The electrometer undergoes yearly calibration at TSI since it serves as the primary reference for characterizing CPC counting efficiency. An example of a 3776 counting efficiency curve from Hermann et al. (2007) is presented in Figure 4.

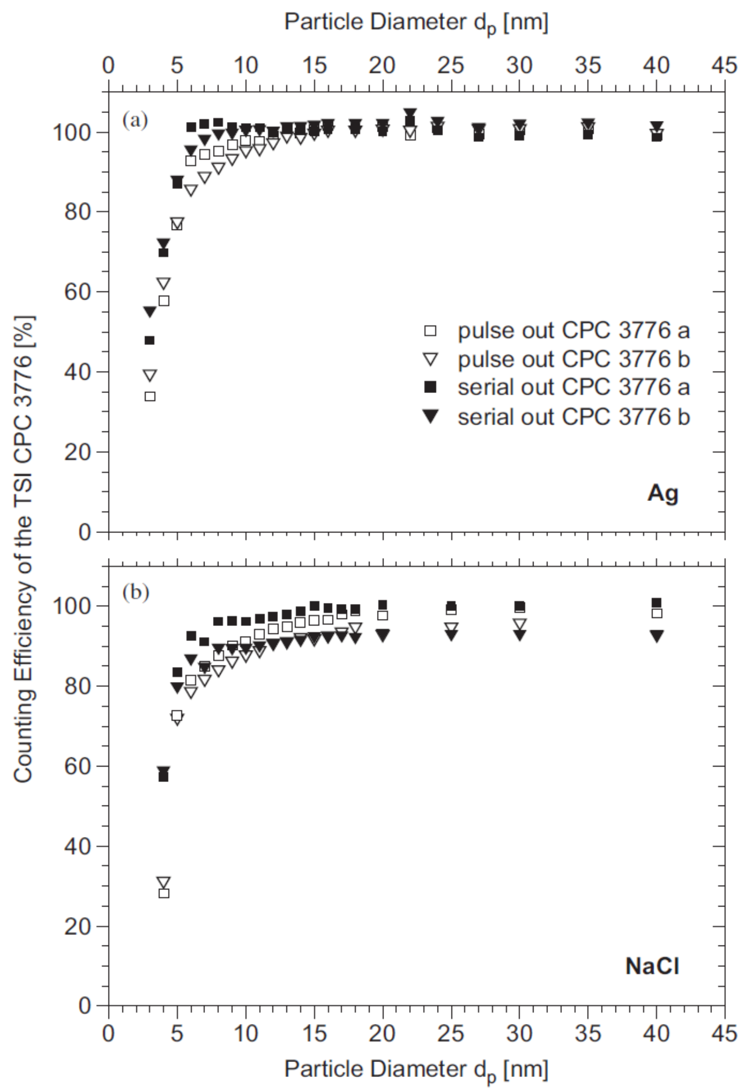

Figure 4. CPC 3776 counting efficiencies for silver (top) and sodium chloride particles (bottom) as presented in Hermann et al. (2007).

13.0 Maintenance

The following maintenance tasks are required for the Model 3776 UCPC:

- Re-fill the butanol reservoir once every three days.
- Drain butanol from the butanol reservoir prior to instrument shipment.
- Correct flooded optics when there is any indication of flooding.
- Clear clogged nozzle when consistent under-counting is observed with respect to a co-located/co-sampling 3772. To effectively unclog the nozzle, briefly (~1 second) obstruct the UCPC inlet (with your finger, for example) to generate a slight under-pressure in the instrument. Repeat three times.

- Verify flow rate once a week: Connect a low-pressure-drop bubble flowmeter to the CPC inlet and record the average of three measurements. The CPC inlet flow rate should be 1.5 ± 0.05 lpm (high-flow mode). The sample or aerosol flow rate is also monitored and kept within 0.05 ± 0.005 lpm.
- Verify zero check once a week: Perform a zero check once a week by employing a HEPA capsule filter at the instrument inlet. A properly functioning CPC should be zero in less than a minute. Failure in the zero check suggests potential issues such as leaks, contamination in the optical chamber, or a dirty wick, among other possibilities.
- Replace the CPC wick at the beginning of the campaign and every 6 to 12 months during continuous use.
- Pre- and post-campaign comparisons and characterizations are carried out in the laboratory to evaluate the CPC's performance. Any notable deviations observed during these tests also aid in identifying potential maintenance or servicing needs in the laboratory. If necessary, the CPC is sent for manufacturer service and calibration.
- Regular factory service and calibration of the CPC at the manufacturer every typically one to two years.

Refer to the manufacturer's website for detailed descriptions of each maintenance action and associated procedures.

14.0 Safety

The UCPC is a Class I laser-based instrument. During normal operation, the user will not be exposed to laser radiation. However, the UCPC uses n-butyl alcohol (butanol) as a working fluid, which is flammable and toxic, if inhaled.

15.0 References

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Appendix A

TSI Model 3776 UCPC

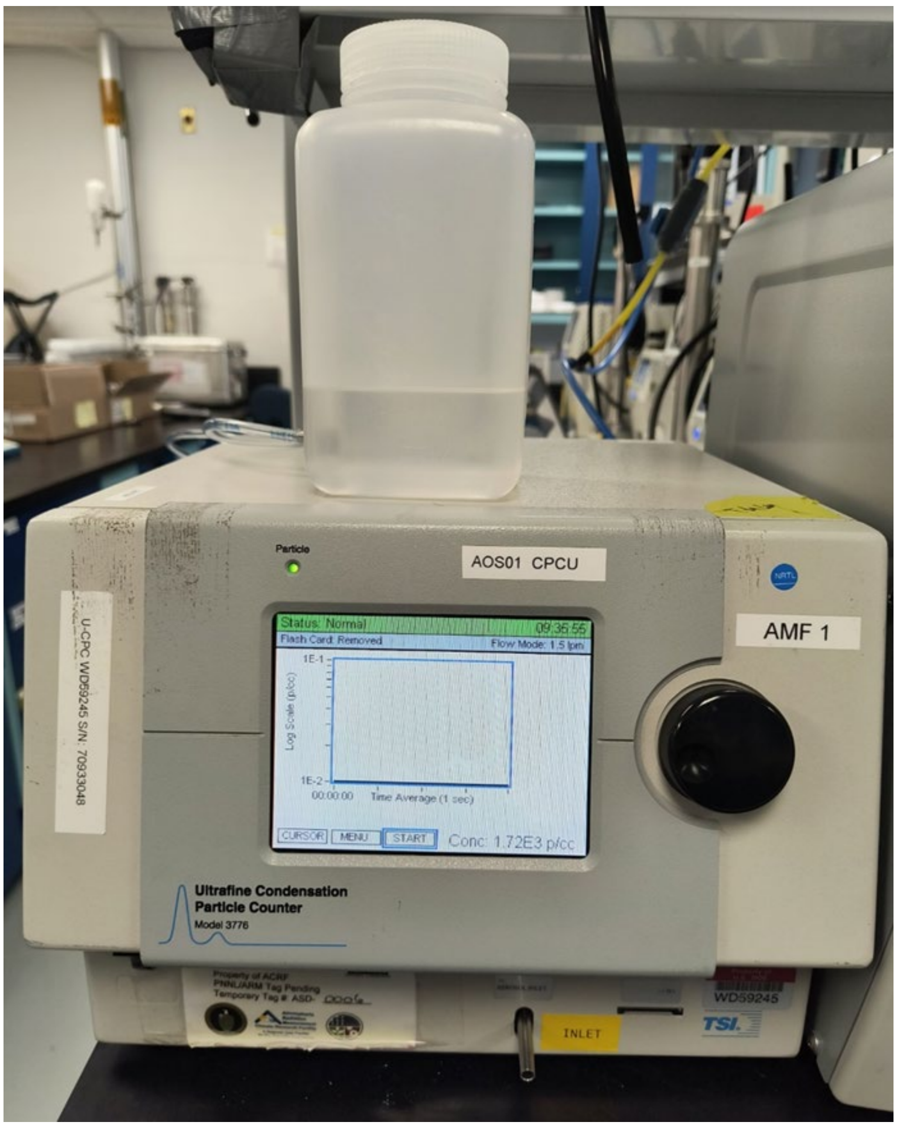

Figure 5. TSI Model 3776 UCPC. Photo courtesy of Brookhaven National Laboratory.

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