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DOE/SC-ARM-TR-145

Condensation Particle Counter Instrument Handbook

C Kuang

February 2016

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

CPC	condensation particle counter
°C	degrees Celsius
#/cc	particle number per cubic centimeter
kPa	kilo-Pascal
lpm	liters per minute
nm	nanometer
UTC	coordinated universal time
yyyy-mm-dd	year-month-day
hh:mm:ss	hours:minutes:seconds
mA	milli-Amperes
sccm	standard cubic centimeters per minute
N	particle number concentration
in. Hg	inches of mercury
RH	relative humidity
ft	feet
atm	atmospheres
m	meters

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1.0 Instrument Title

Model 3772 Condensation Particle Counter (pictured in Appendix A; more resources on manufacturer's website)

2.0 Mentor Contact Information

Chongai Kuang
Biological, Environmental & Climate Sciences Department
Brookhaven National Laboratory
Building 815 E
Upton, NY 11973
USA
(631) 344-7257
ckuang@bnl.gov

3.0 Vendor/Developer Contact Information

Vendor:
TSI Incorporated
500 Cardigan Road
Shoreview, MN 55126
USA
(651) 490-2811

Product Support Specialist:
Maynard Havlicek
TSI Incorporated
500 Cardigan Road
Shoreview, MN 55126
Office: (651) 490-4075
mh@tsi.com

4.0 Instrument Description

The Model 3772 CPC is a compact, rugged, and full-featured instrument that detects airborne particles down to 10 nm in diameter, at an aerosol flow rate of 1.0 lpm, over a concentration range from 0 to 1×10^4 #/cc. This CPC is ideally suited for applications without high concentration measurements, such as basic aerosol research, filter and air-cleaner testing, particle counter calibrations, environmental monitoring, mobile aerosol studies, particle shedding and component testing, and atmospheric and climate studies.

5.0 Measurements Taken

The primary CPC measurement output is the particle number concentration; measured in units of #/cc. Additionally, the following measurements are also recorded: instrument error code, instrument temperatures (saturator, condenser, optics, and cabinet), instrument pressures (ambient, orifice, and nozzle), the laser current, and working fluid liquid level. An installed dilution flow system provides user-set dilution flow to the CPC sample inlet, so high aerosol number concentration measurements (> $1x10^4$ #/cc) and dilution flow rate can be recorded after applying a dilution correction.

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

CPC output data 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 (open/closed), dilution flow set point (sccm), dilution flow measured (sccm), and aerosol flow rate (empty field). Output data is stored on the instrument computer and recorded at a time resolution of one second and written to text files spanning an interval of one hour. Please note, this data object description is subject to revision.

If dilution flow ($Q_{dilution}$, units of sccm) is utilized during sampling, then the ambient particle concentration ($N_{ambient}$) is obtained by correcting the output measured particle concentration ($N_{measured}$) for the effect of dilution, according to the following formula:

$$N_{ambient} = N_{measured} \cdot \left[\frac{1000}{1000 - Q_{dilution}} \right].$$

6.2 Data Ordering

Data from the Model 3772 CPC can be accessed and ordered on the ARM website. Data is organized by measurement location.

6.3 Data Plots

A plot of representative Model 3772 CPC data is presented in Figure 1. Particle number concentration measurements are presented as a function of sampling times for typical measurements obtained during the GoAmazon field campaign on 13 October 2014.

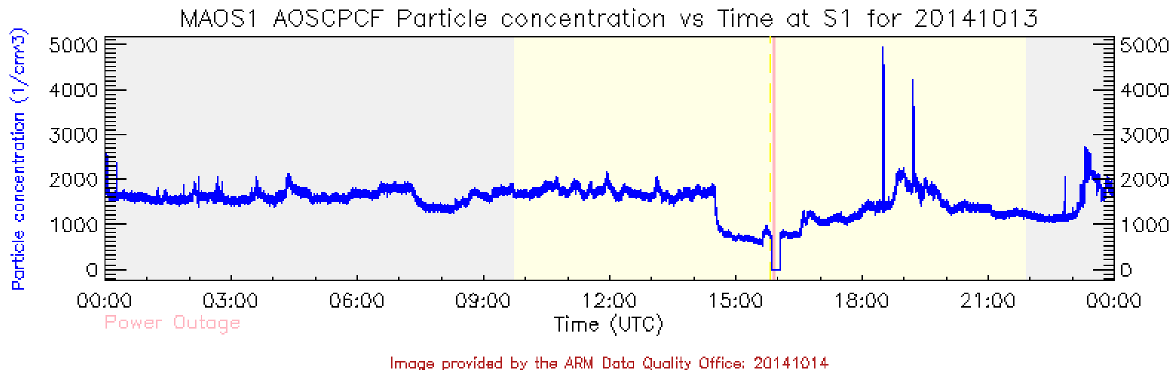


Figure 1 Data plot of aerosol number concentrations, as measured by the Mobile Aerosol Observing System (MAOS) Model 3772 CPC deployed at Manacapuru, Brazil during the GoAmazon campaign on 13 October 2014. Plot was generated using the ARM Program Data Quality Diagnostic Plot Browser (http://plot.dmf.arm.gov/plotbrowser/).

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 meta-data such as instrument housekeeping) falls above, below or outside defined maximum threshold ranges. Examples of these thresholds and ranges are listed below; intended to be illustrative, rather than definitive.

- Maximum nozzle pressure = 3 kPa: The nozzle pressure is a measure of the pressure drop across the nozzle and indicates the degree to which the nozzle is clogged by debris. Nozzle pressures in excess of 3 kPa will generate a warning.
- Minimum orifice pressure = 50 kPa: The orifice pressure is a measure of 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 to produce 1 lpm flow. Orifice pressures below 50 kPa will generate an alarm.
- Nominal saturator temperature range = 38.5°C – 39.5°C: Operating outside this temperature range results in a deviation from expected butanol vapor pressure and resulting particle size detection limit (nominally 10 nm in diameter). Saturator temperatures outside this range will generate an alarm.
- Nominal condenser temperature range = 21.5°C – 22.5°C: Operating outside this temperature range results in a deviation from the expected vapor saturation ratio and resulting particle size detection limit (nominally 10 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: Operating below this fill level may prevent sufficient butanol vapor from reaching 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 = 35 mA: Operating beneath this current value indicates declining laser health. Laser currents below this limit will generate an alarm.

The second level of data quality evaluation involves the automatic generation of the following plots, in collaboration with the Data Quality Office:

- Nozzle pressure as a function of time: a steady increase in the nozzle pressure over time indicates the nozzle is clogged and requires cleaning (see Appendix B for nozzle cleaning procedures).
- Comparison of co-located 3772 and 3776 particle number concentration measurements as a function of time: the 3772 particle number concentration should always be equal to, or smaller, than the 3776 particle number concentration, since the 3772 particle size detection limit is 10 nm and the 3776 particle size detection limit is 3 nm. A measurement comparison from both CPCs provides a quick assessment of relative CPC performance.

6.5 Calibration Data Base

The Model 3772 CPC and accompanying dilution flow system are calibrated prior to instrument installation and deployment. Calibration activities include verifying inlet flow rate with a low pressure-drop bubble flow meter, calibrating the dilution flow system, and determining the size-dependent particle counting efficiency, according to methods defined in Hermann et al (2007) and Mordas et al (2008). CPC calibration data is collected and maintained by the instrument mentor.

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 particle number concentration range is 0 to $1x10^4$ #/cc.

7.3 Accuracy

Since the inlet flow rate is controlled by a critical orifice at 1 lpm, the particle concentration accuracy is strictly a function of statistical noise associated with single particle counting and, 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 2.5%, while a concentration measurement typical of polluted environments (~5000 #/cc) has an accuracy of 0.3%. However, in the field, the inlet flow rate (which is not an on-line measurement) typically has variability of up to 5%, which is the primary contributor to measurement accuracy.

7.4 Repeatability

Since the inlet flow rate is fixed by a critical orifice, the particle concentration repeatability is a function of statistical noise associated with single particle counting and, therefore, concentration-dependent. Using a typical sampling time of one second, successive concentration measurements typical of clean environments (~100 #/cc) have a repeatability within 2.5% of each other, while successive concentration measurements typical of polluted environments (~5000 #/cc) have a repeatability within 0.3% of each other. However, in the field, the inlet flow rate (which is not an on-line measurement) typically has variability of up to 5%, which is the primary contributor to measurement repeatability.

7.5 Sensitivity

Particle counting sensitivity, respective to the sampled aerosol amount (concentration linearity), is accounted for in the signal-processing electronics. Particle concentrations are corrected for concentration-dependent counting coincidence, up to concentrations of $1x10^4$ #/cc.

7.6 Uncertainty

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

$$\sigma_r = \frac{\sqrt{n}}{n}.$$

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

$$concentration = \frac{n}{Q \cdot t}$$

Where t is the sampling time interval.

7.7 Output Values

Output data from the CPC 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 (open/closed), dilution flow set point (sccm), dilution flow measured (sccm), and aerosol flow rate (empty field).

8.0 Instrument System Functional Diagram

The 3772 CPC consists of three systems: 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 2.

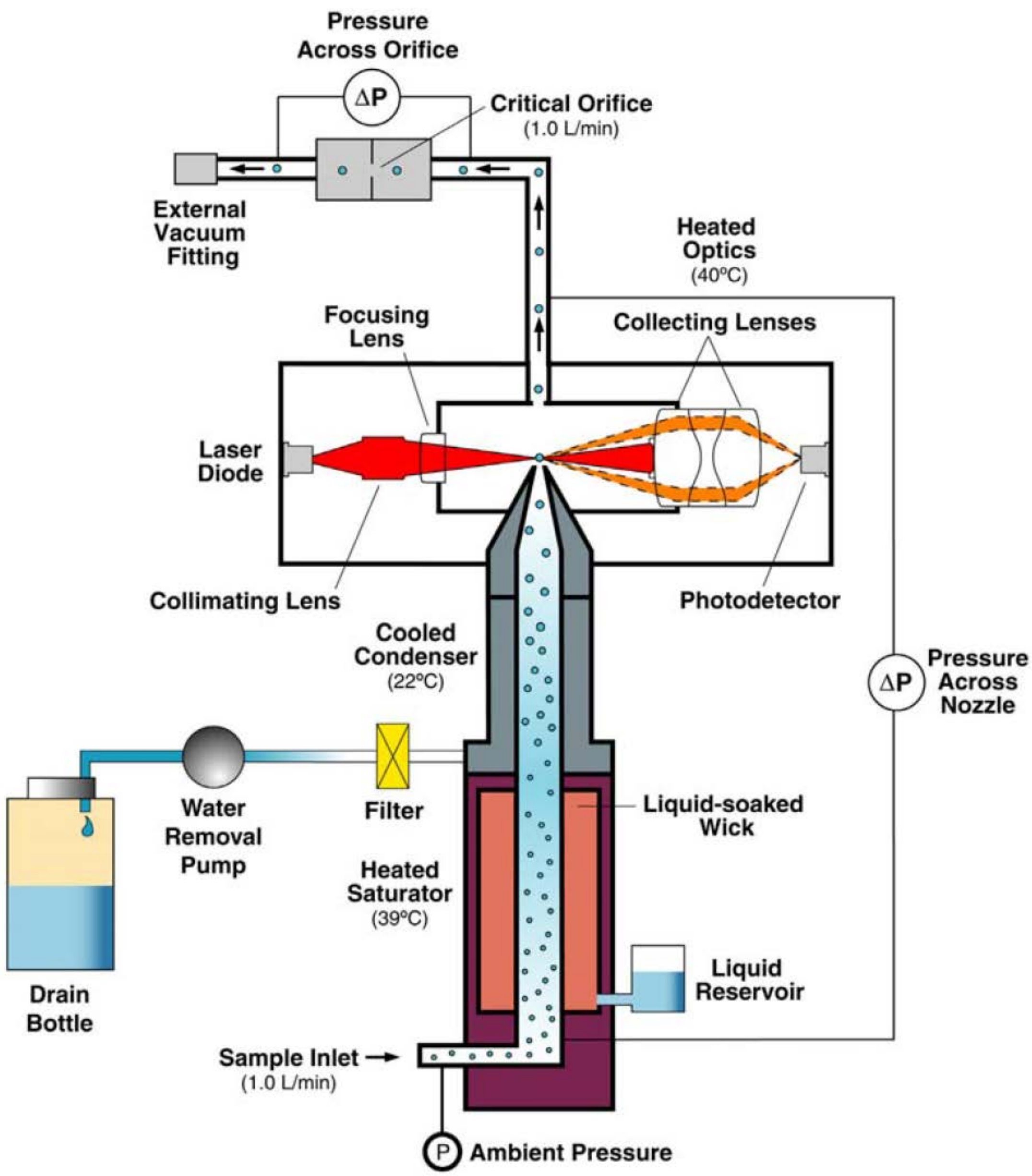


Figure 2. Flow schematic of the Model 3772 CPC, adapted from the manufacturer's manual

The sensor grows the sampled particles into larger droplets, which are detected optically. Laminar aerosol flow is sampled through the inlet and enters the saturator, where butanol liquid is evaporated from a heated wick, and saturates the aerosol flow with butanol vapor. The combined flow of aerosol and butanol vapor then enters the condenser, which is cooled with a thermo-electric device. There, the butanol vapor becomes super-saturated and condenses onto the aerosol particles to form larger droplets. These 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 electrical pulses are counted and, at high particle concentrations, corrected for particle coincidence.

9.0 Instrument/Measurement Theory

As the instrument name indicates, the essential feature of the CPC is the growth of sampled particles through working fluid condensation, followed by optical counting. When the vapor surrounding particles reaches a certain degree of super-saturation, the vapor begins to condense on the particles; a phenomenon called heterogeneous nucleation. If the super-saturation levels are too high, however, vapor condensation can take place even without sampled particles present; a phenomenon called homogeneous nucleation in which molecules of the working fluid vapor collide and form clusters. Particle counts from droplets generated through homogeneous nucleation of the working fluid result in instrument noise and should be avoided. Optimal CPC 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 operating value of the super-saturation ratio and can be calculated from theoretical predictions of particle diameter and vapor super-saturation ratio (Ahn and Liu 1990; Stolzenburg and McMurry 1991).

10.0 Setup and Operation of Instrument

Setup Instruction 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 to 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 Model 3772 CPC uses reagent-grade 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 then plug 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 CPC by turning on the switch next to the power cord on the back panel. The instrument will then begin a warm-up sequence, which lasts approximately ten minutes. Wait until the warm-up sequence is completed before using.
5. An external vacuum source must be connected to the external CPC vacuum port (located in the lower right-hand corner of the CPC back panel) before particles can be sampled. The vacuum source should provide at least 60 kPa (18 in. Hg) of power, resulting in a fixed 1.0 pm critical flow.
6. Place the CPC on a level surface. Ensure the cooling fan on the back panel of the CPC is exposed to ambient air. Then, connect the black sampling tubing to the CPC inlet tube.

The Model 3772 CPC 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% RH non-condensing.

During ARM deployments, the 3772 CPC samples within an environmentally controlled measurement container, according to the manufacturer's environmental requirements. For further details and instructions, please consult the manufacturer's website for additional resources.

11.0 Software

Data acquisition and instrument control is accomplished with 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 CPC and listed in the manufacturer's manual.

12.0 Calibration

The Model 3772 CPC undergoes calibration prior to installation in order to characterize the inlet flow rate, dilution flow system, 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 1.0 lpm with a variability of ±5%.

The dilution flow system is comprised of dried, compressed air and a mass flow controller. Dilution flow is measured with a bubble flow meter and calibrated against the mass flow controller set point. An example flow calibration data sheet is included in Appendix C.

The 3772 CPC has a nominal D_{50} of 10 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 particle composition (to some extent); which can be 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 Electrostatic Classifier and Model 3085 Nano Differential Mobility Analyzer. The counting efficiency is calculated by comparing CPC readings to a TSI Model 3068A Aerosol Electrometer. An example 3772 counting efficiency curve from Hermann et al (2007) is presented in Figure 3.

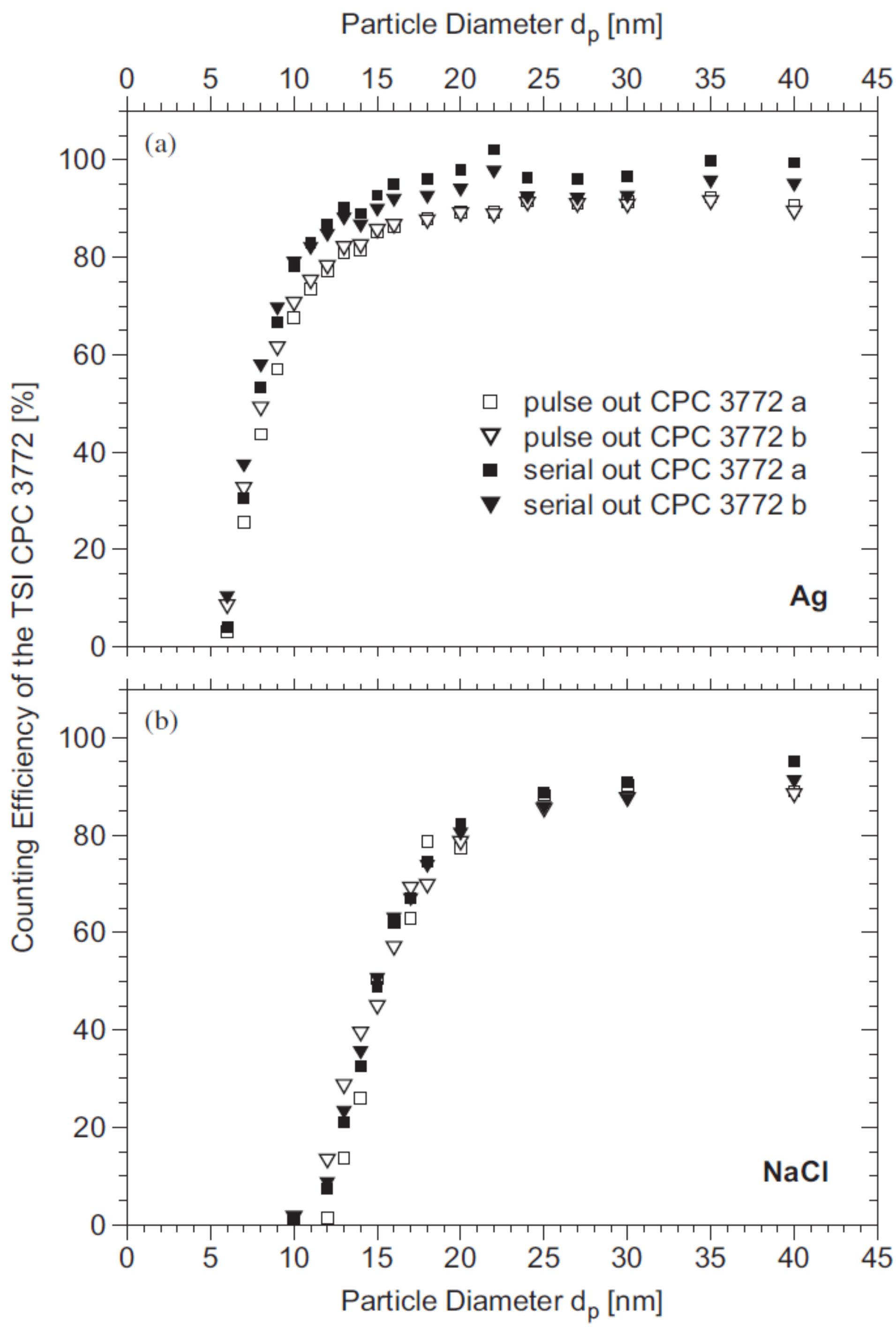


Figure 3. CPC 3772 counting efficiencies for (a) silver and (b) sodium chloride particles, as presented in Hermann et al (2007)**.**

13.0 Maintenance

The following maintenance procedures are required:

- Re-fill butanol reservoir once every three days.

- Drain butanol from the butanol reservoir prior to instrument shipment.
- 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 flow rate should be 1.0 lpm with a variability of ±5%.
- Correct flooded optics whenever there is indication flooding has occurred.
- Clean clogged nozzle when nozzle pressure is > 3 kPa and has been steadily increasing over time. Note: While this procedure is not included in the manufacturer’s manual, it is included as a separate document.

Refer to the manufacturer’s manual in Appendix D for a detailed description of the procedures associated with each maintenance action.

14.0 Safety

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

15.0 Citable References

Hermann, M., B Wehner, O Bischof, HS Han, T Krinke., W Liu., A Zerrath, and A Wiedensohler. 2007. “Particle counting efficiencies of new TSI condensation particle counters.” *Journal of Aerosol Science* 38:674-682.

Mordas, G., H Manninen, T Petäjä, P Aalto, K Hämeri, and M, Kulmala. 2008. “On operation of the ultra-fine water-based CPC TSI 3786 and comparison with other TSI models (TSI 3776, TSI 3772, TSI 3025, TSI 3010, TSI 3007).” *Aerosol Science and Technology* 42:152-158.

Ahn, K. H. and BYH Liu. 1990. “Particle activation and droplet growth processes in condensation nucleus counter I. Theoretical background.” *Journal of Aerosol Science* 21:249-261.

Stolzenburg, M. R. and PH McMurry. 1991. “An ultrafine aerosol condensation nucleus counter.” *Aerosol Science and Technology* 14:48-65.

Appendix A: CPC Image

Figure 4. Condensation Particle Counter

Appendix B: Addendum to TSI Condensation Particle Counter Model 3772 Nozzle Cleaning Procedure

VII.11 Brad Flowers, Los Alamos National Laboratory

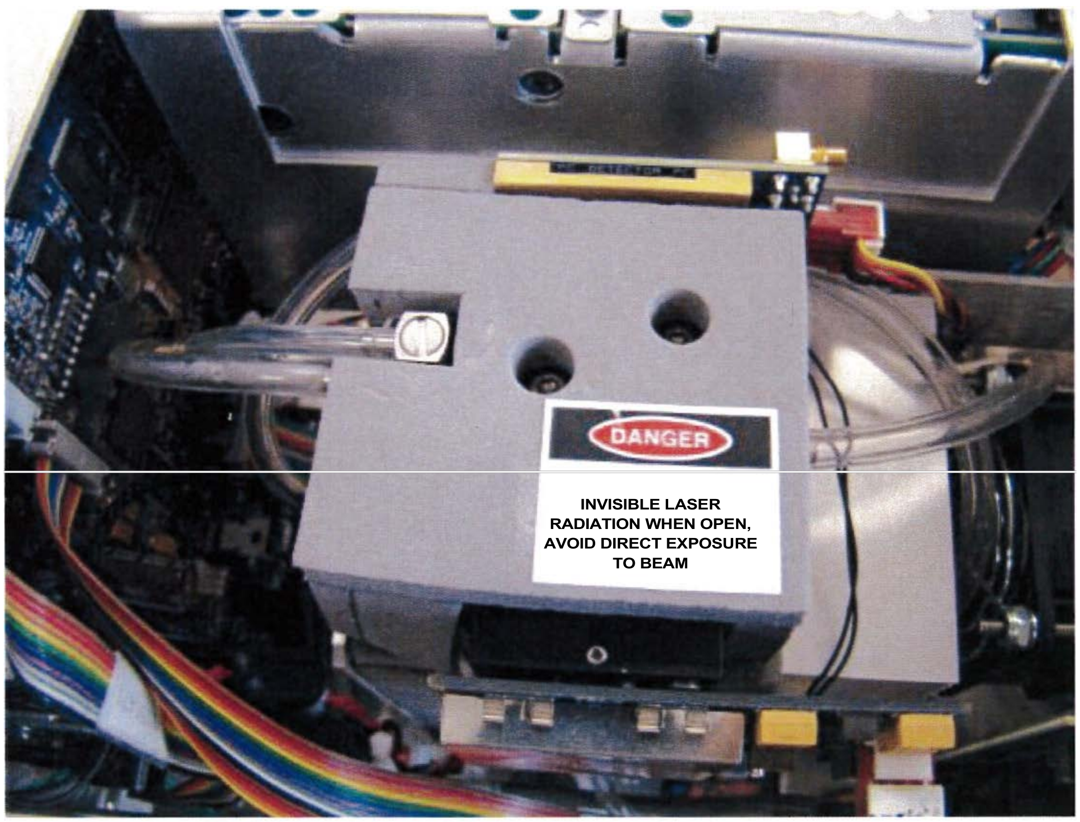
From Connie Rettig, TSI Technician, 21 February 2011

Nozzle pressure should be 2-3.

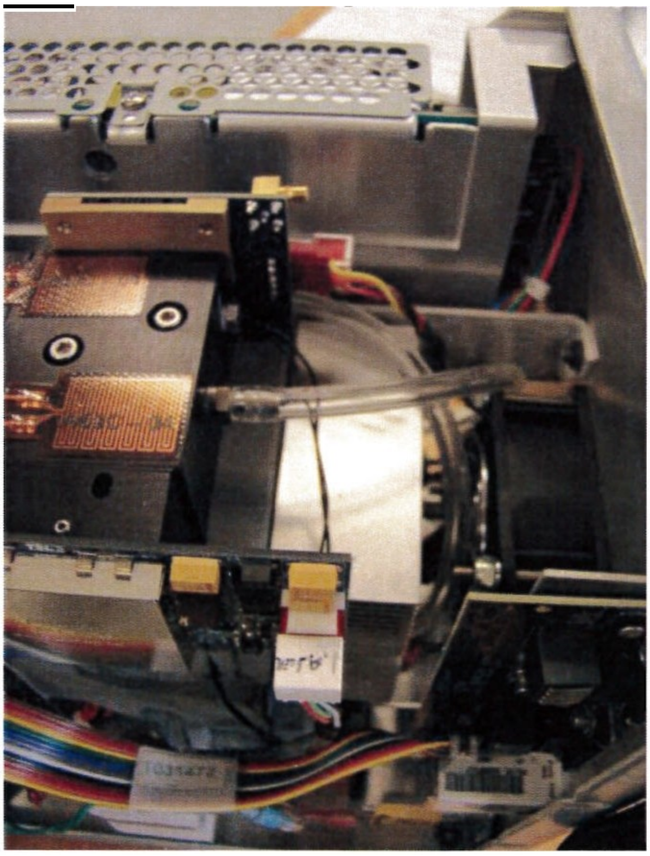
Clean Nozzle: The nozzle resides on the bottom of the laser block. Remove the two top screws (7/ 64). Use a small screw-driver to pry out the nozzle. Inspect for debris and clean by blowing with compressed air and using isopropyl alcohol as needed.

CAUTION. Be careful of tubing, wiring, and laser."

1. Remove Insulation



2. Uplug Cable 1and Cable 2 on top of laser block.



Appendix C: MAOSA 3772 Dilution Flow Calibration

ARRA MFCs 140828.xlsx
Sheet: MAOS-A CPC Dil 5
Page 1 of 1

Flow Calibration Data Sheet:

MFC/Inst:	MAOS-A CPC 3772 Dil.	Operator:	SRS
Calibration:	5	Date:	8/12/2014
SN/MN:	0002 MDD-52CRS0020N-01	Cal. Instrument:	Gil. 105743-S
Nom Rng:	0-2 SLPM	Flow Tube:	20 sccm-6 LPM
		Location:	MAOS-A/MAO

n	Time (hh:mm)	Flow Set	Flow Read (nominal) (sccm)	V meas (sccm)	V dry 0˚C, 1 atm (sccm)
1	19:36	400	400±0.2	478.5	415.1
2		400		480.5	416.8
3		400		481.0	417.3
4		800		932.8	809.2
5		800		931.9	808.4
6		800		931.6	808.2
7		1200		1383.0	1199.8
8		1200		1379.0	1196.3
9		1200		1377.0	1194.5
10		1600		1821.0	1579.7
11		1600		1822.0	1580.6
12		1600		1823.0	1581.5
13		900		1034.0	897.0
14		900		1035.0	897.9
15		900		1035.0	897.9
16					0.0
17					0.0
18					0.0
19					0.0
20					0.0
21					0.0
22					0.0
23					0.0
24					0.0
					0.0
1					0.0
2					0.0
3					0.0
4					0.0
5					0.0

Tinitial	27.3 ˚C
Tinstrument	T2 Racck 1
Pinitial	1003.1 hPa
Pinstrument	WXT-520
P(H2O)	36.3 hPa

Fit to Y=a+bx

Confidence Interva	0.95
n	15
Degrees Freedom	13
Student t	2.1604
x avg	980
a	980.01
b	0.9708
s	3.4998
s(a)	0.90365
s(b)	0.00225
LCC (R)	0.99997
y-int	28.6194
C.I. y-int	5.14403
slope	0.97081
C.I. slope	0.00486

CPC flow 970
28.6 C
1020 hPa

Reading with no flow (%)

x	970
S.D.	#DIV/0!
MFC set	420.159

Record only new data for each row — Dil Factor 0.5

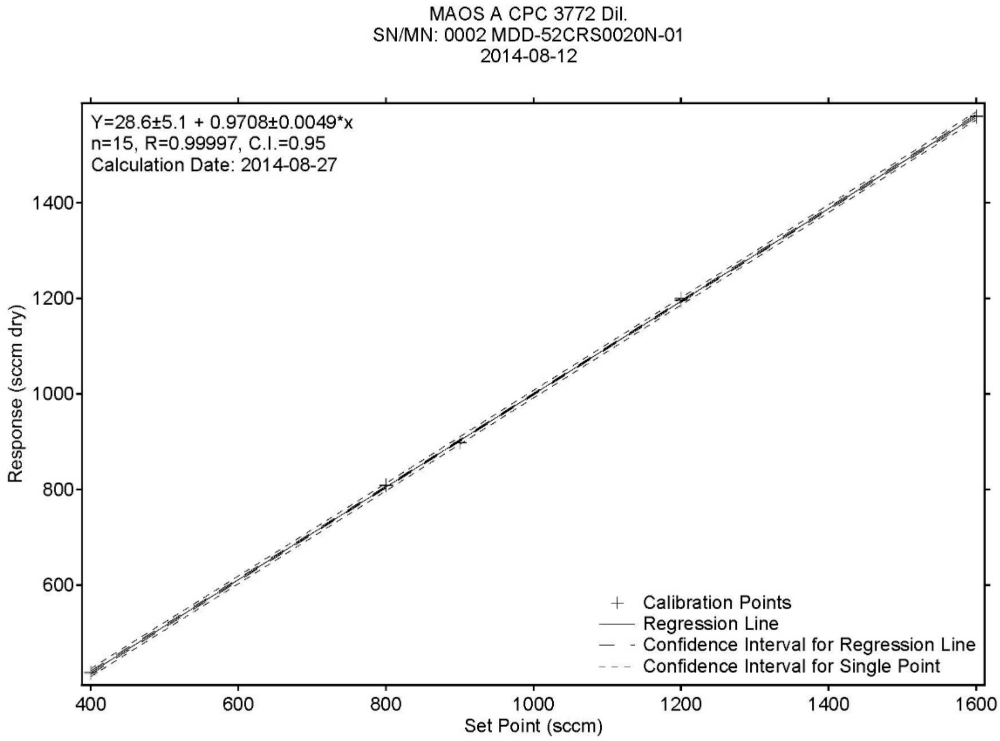
Notes:

Ran MFC with CPC vi. Used Pentras air dryer flow. .

.Couldn't go above ~1800 sccm with available pressure.

~CPC flow measured by C.K. P = ? hPa, T=? C. No H2O correction.

CPC dil returned to 422.1 sccm at end of calibration


MAOS A CPC 3772 Dil.
SN/MN: 0002 MDD-52CRS0020N-01
2014-08-12
Y=28.6±5.1 + 0.9708±0.0049*x
n=15, R=0.99997, C.I.=0.95
Calculation Date: 2014-08-27
Response (sccm dry)
Set Point (sccm)
Calibration Points
Regression Line
Confidence Interval for Regression Line
Confidence Interval for Single Point

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