U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-TR-257

Advanced Mixing Condensation Particle Counter (aMCPC) Instrument Handbook

F Mei
L Goldberger

November 2020

ARM

DISCLAIMER

This report was prepared as an account of work sponsored by the U.S. Government. Neither the United States nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

DOE/SC-ARM-TR-257

Advanced Mixing Condensation Particle Counter (aMCPC) Instrument Handbook

F Mei
L Goldberger
Both at Pacific Northwest National Laboratory

November 2020

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

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACCESS	aerosol counting, composition, extinction, and sizing system
ADC	ARM Data Center
ARM	Atmospheric Radiation Measurement
ASCII	American Standard Code for Information Interchange
CPC	condensation particle counter
DAQ	data acquisition
DMA	differential mobility analyzer
G-1	Gulfstream-159
HEPA	high-efficiency particulate air
MIST	multiple instrument stackable tower
MOPC	miniaturized optical practical counter
netCDF	Network Common Data Form
RH	relative humidity
STAP	single-channel tricolor absorption photometer
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UTC	Coordinated Universal Time
VDC	volts direct current

Contents

Figures

Tables

1.0 Instrument Title

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's aerosol counting, composition, extinction, and sizing system (ACCESS) includes a base module (9400), a filter sampler (9401), an advanced mixing condensation particle counter (aMCPC, 9403), a miniaturized optical practical counter (MOPC, 9405), and a single-channel tricolor absorption photometer (STAP, 9406).

This handbook focuses on the aMCPC, which measures the ultra-fast total aerosol particle number concentration at 180 ms response rate with a detection diameter (D_{50} = 7 nm).

2.0 Mentor Contact Information

Fan Mei
Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K4-28
Richland, Washington 99352
Tel: 509-375-3965
fan.mei@pnnl.gov

3.0 Vendor/Developer Contact Information

Fred Brechtel
1789 Addison Way
Hayward, California 94544
Tel: 510-732-9723
https://www.brechtel.com

4.0 Instrument Description

The Model 9403 aMCPC, as shown in Figure 1, is a compact particle counter with a response time of 180 ms, which allows it to perform ultra-fast total particle number concentration measurements. The compact size of this unit makes it suitable for applications like onboard unmanned aerial vehicles (UAV) and other mobile platforms where high time resolution is critical, but space is limited. The aMCPC can partner with a rapid particle size scanning technique (such as differential mobility analyzer [DMA]) to provide aerosol particle size distribution. This unit can operate at two aerosol flow rates – 0.36 and 0.72 lpm.

Figure 1. aMCPC photo from the manufacturer's website (https://www.brechtel.com/products-item/particle-counter/)

5.0 Measurements Taken

The aMCPC grows sampled aerosol particles into optically detectable particle size using butanol vapor. The turbulent mixing process results in much faster response times than other laminar-flow condensation particle counters (CPCs) and leads to a high-time-resolution aerosol total number concentration measurement. The detectable size range is 7–2,000 nm diameter, with D_{50} = 7.0 nm. The maximum concentration measurable is up to 10^5 cm^{-3}. Coincidence corrected concentration uncertainty at the maximum concentration is ± 8%. Note that the turbulent mixing does not result in particle loss because the droplet Stokes numbers are too low to cause the condenser's inertial deposition.

6.0 Links to Definitions and Relevant Information

Product website: https://www.brechtel.com/products-item/particle-counter/

Instrument webpage from arm.gov: https://www.arm.gov/capabilities/instruments/cpc-air

6.1 Data Object Description

The raw data from the aMCPC are recorded in *.dat file with appropriate headers specifying the data and units of measurement. The diameter array is written as one of the header rows in the file. The data file column definitions are included in Table 1.

The ARM archived data are available in both netCDF format and ASCII format.

Table 1. Data file column definitions.

Variable names	Description
YY/MM/DD HR:MN: S.C.	Time, UTC
aveconc	Average concentration for saved interval, cm^{-3}
concent	Coincidence corrected concentration, cm^{-3}
rawconc	Raw uncorrected concentration, cm^{-3}
cnt_sec	Count per second
condtmp	Condenser temperature, ℃
satttmp	Saturator temperature, ℃
satbtmp	Saturator back temperature, ℃
optctmp	Optics temperature, ℃
inlttmp	Inlet temperature, ℃
smpflow	Sample flow rate, cc/min
satflow	Saturator flow, cc/min
pressur	Pressure, mBar
condpwr	Condenser cooler power, 0-250
sattpwr	Saturator top heater power, 0-200
satbpwr	Saturator bottom heater power, 0-200
optcpwr	Optics block heater power, 0-200
satfpwr	Saturator flow pump power, 0-200
exhfpwr	Exhaust fan power, 0-200
fillcnt	Butanol fill attempts
err_num	Error code, all errors OR'd together
mcpcpwr	aMCPC power, 0-250
mcpcpmp	aMCPC pump power, 0-200

6.2 Data Ordering

Data can be ordered at the ARM Data Center (ADC) via ADC Data Discovery. Data are organized by measurement location and campaign.

6.3 Data Plots

Figure 2 shows the housekeeping data from the aMCPC recorded by the Brechtel software. The ARM Aerial Facility (AAF) flight operation crew uses this type of figure in the field to monitor the performance of aMCPC.

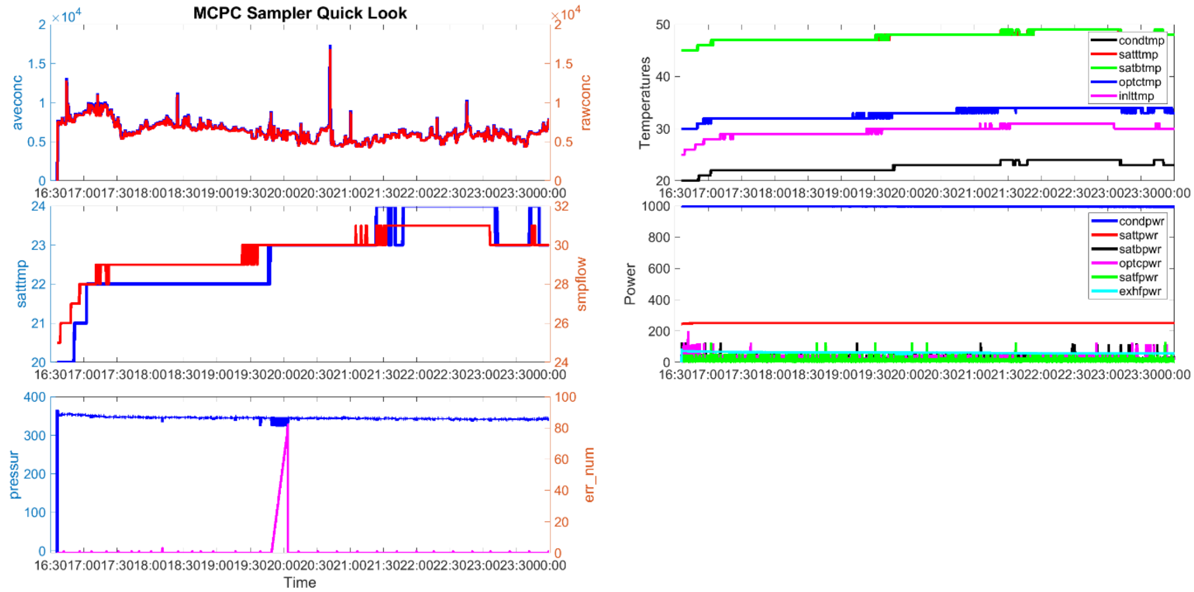

Figure 2. Housekeeping data recorded in the lab from the aMCPC.

6.4 Data Quality

The typical average ratio of the aMCPC to a reference CPC concentration was 0.998, with a standard deviation of 0.013 based on the manufacturer's manual. Our unit was compared with a laminar-flow CPC (CPC 3772) in the laboratory (shown in Figure 3) and in-flight onboard ARM's Gulfstream-159 (G-1) aircraft.

During the bench testing, the aerosol particles were sampled from the ambient inlet, which was 10 m above the ground. Figure 3 demonstrates excellent agreement between the two CPCs. During the in-flight operation, as shown in Figure 4, a HEPA filter was installed in the inlet line between 12:07 and12:12. We observed that both units' total number concentrations dropped to zero instantly, then went back to normal after the filter was removed. This test was done with about 200 mbar pressure difference between the inlet and the cabin pressure and demonstrates no internal leakage for operating both units under pressure difference.

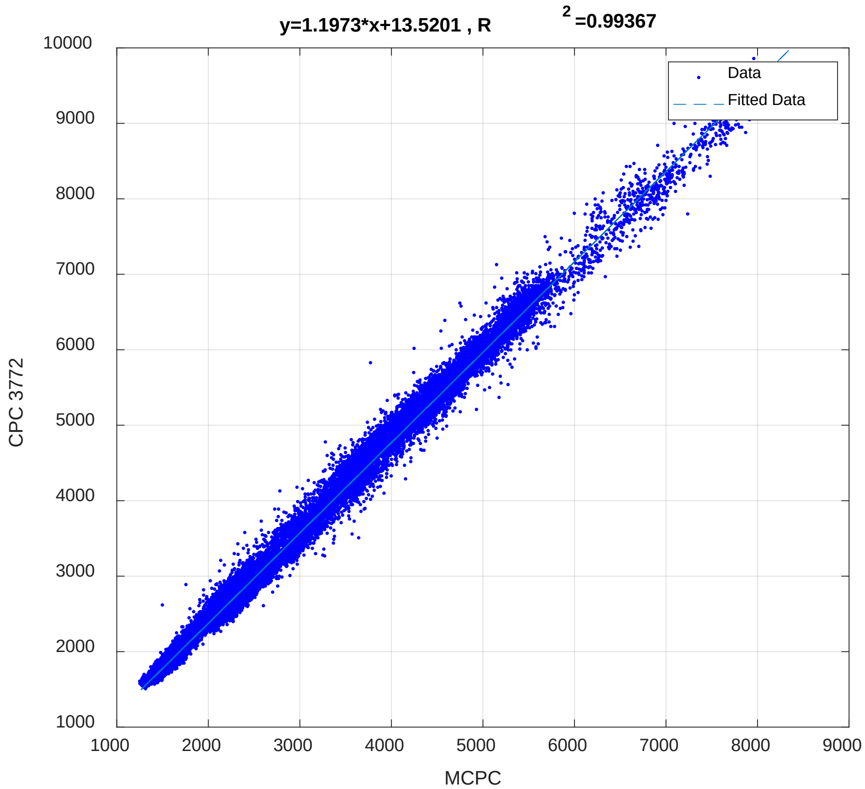

Figure 3. aMCPC and CPC 3772 total number concentration comparison during the bench testing on 8/2/2019.

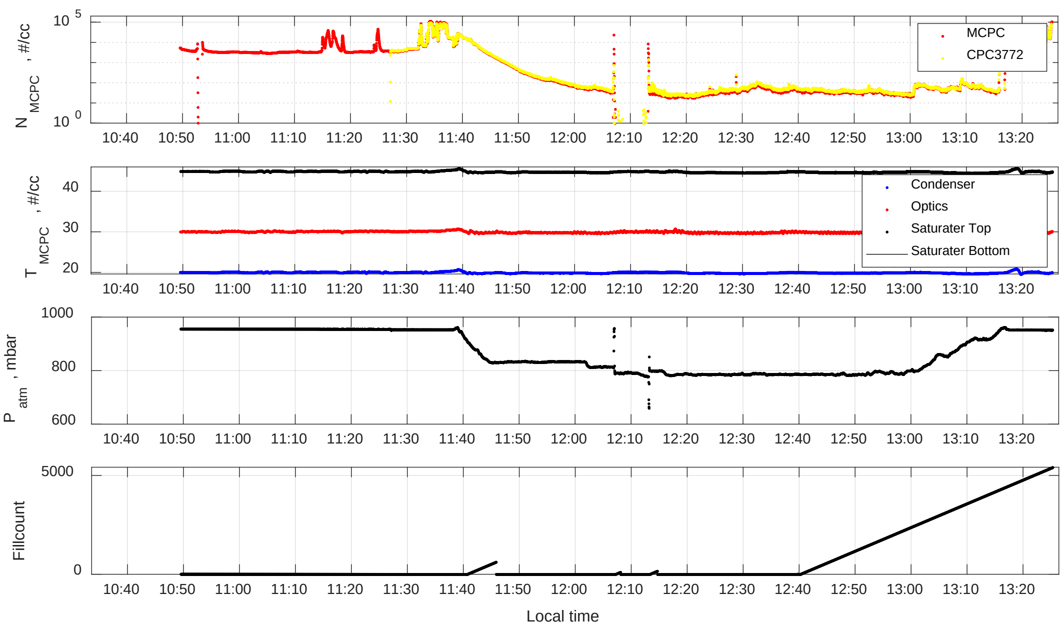

Figure 4. aMCPC operated with CPC 3772 inside the G-1 cabin. Both performance and housekeeping were monitored.

6.5 Calibration Database

The aMCPC is calibrated as any CPC. Calibration activities include verifying the 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). aMCPC calibration data is collected and maintained by the instrument mentor.

7.0 Technical Specification

Table 2. Technical specification.

PARAMETER	VALUE
D50	7.0 nm
Particle size range	7-2,000 nm diameter
Maximum concentration	100,000 cm^{-3}
Coincidence corrected concentration uncertainty @ 100,00/cc	+/- 8%
Sample flow	0.36 or 0.72 lpm
Response time	180 milliseconds
Background	<0.001 cm^{-3}
Butanol use	1.9 ml/hr
Reservoir capacity	250 ml (1000 ml available)
Data output	RS-232, BNC
Operating pressure range	0.2-1.0 atm [NOTE1]
Operating temperature range	-20°C to 38°C
Operating humidity range	0 - 95% RH non-condensing [NOTE2]
Size	5.8 x 8 x 5.3 in/14.7 x 20.3 x 13.5 cm
Weight	6 lbs/2.7 kg
Supply voltage	12 VDC
Power	50 watts

7.1 Input Values

Before initialization, the following calibration values must be checked:

- Sample slope and offset
- Saturator slope and offset
- Calibration temperature
- Coincidence
- C.S. difference
- Pressure slope and offset.

7.2 Units

The measured quantity of interest is the particle number concentration, measured in units of particles per cubic centimeter (cm^{-3}).

7.3 Range

The particle number concentration range is 0 to $1x10^5$ cm^{-3}.

7.4 Accuracy

Since the inlet flow rate is typically controlled at 0.36 lpm, 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 cm^{-3}) has an accuracy of 4.0%. A concentration measurement typical of polluted environments (~5000 cm^{-3}) has an accuracy of 0.6%. However, in the field, the inlet flow rate (which is not an online measurement) typically varies up to 5%, which is the primary contributor to measurement accuracy.

7.5 Repeatability

Since the inlet flow rate is controlled by a laminar flow element response loop, 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 clean environments (~100 cm^{-3}) have repeatability within 4.0% of each other. In contrast, successive concentration measurements typical of polluted environments (~5000 cm^{-3}) have repeatability within 0.6% of each other. However, in the field, the inlet flow rate (which is not an online measurement) typically has a variability of up to 5%, which is the primary contributor to measurement repeatability.

7.6 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 $1x10^5$ cm^{-3}.

7.7 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 flow rate. The relative statistical counting error is calculated from the total count, 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.

7.8 Output Values

See the description in section 6.1.

8.0 Instrument System Functional Diagram

Figure 5 shows the schematic of the aMCPC system (Wang et al. 2002). A small internal pump creates the saturator airflow of 0.36 lpm and pushes it through a heated saturator containing warm liquid butanol. An external vacuum pump is used to draw 0.72 lpm flow through a critical orifice from the optical block and provide an additional 1.8 lpm of filtered dilution airflow. The 0.36 lpm of particle sample flow is monitored by a laminar flow element and injected into the saturator flow after it has entered the condenser and rapidly produces the butanol supersaturation field, which initiates particle growth.

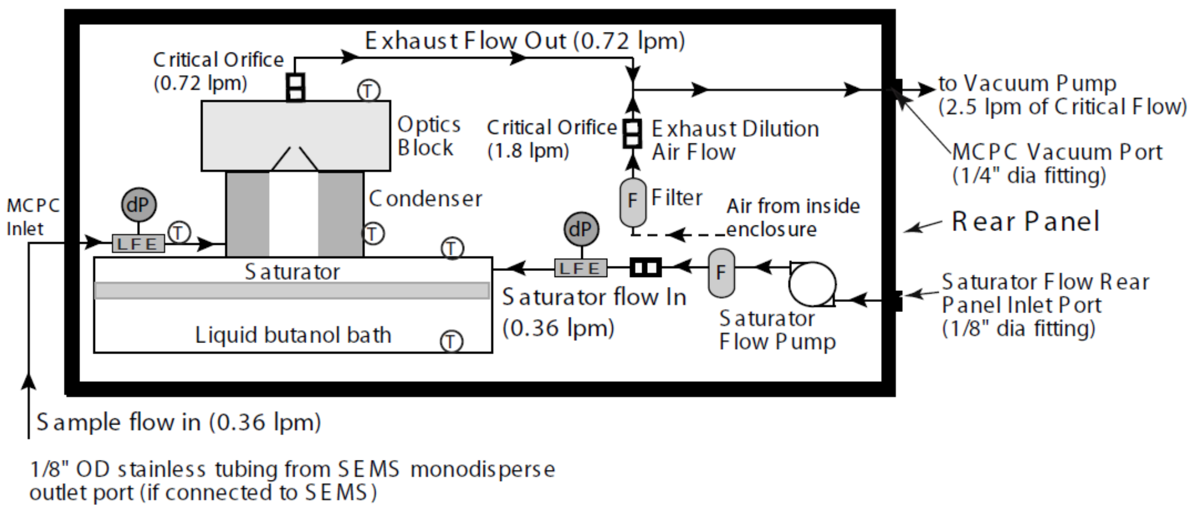

Figure 5. Schematic of the aMCPC system from the manufacturer's manual.

9.0 Instrument/Measurement Theory

The size-dependent counting efficiency of the aMCPC has been quantified at the manufacture using DMA-selected monodisperse particles with diameters from 4–80 nm. The general equation describing the detector size-dependent response takes the form:

$$\eta = 1.0 - \frac{C_0}{1+e^{\frac{D_p - C_1}{C_2}}} \quad (1)$$

Where the best-fit parameter for the aMCPC are C_0= 1.05, C_1 =5.5, and C_2 =0.95.

For the AAF unit, we confirmed that D_{50} =7 nm.

Coincidence occurs when the sampling concentrations are too high, and more than one particle is presented within the optical scattering volume at the CPC time response interval. To improve the accuracy of measurement, the measured concentrations can be corrected for coincidence using the equation (2) below.

$$N_a = N_i e^{N_a Q_{det} \tau_{det}} \quad (2)$$

Where: N_a is the actual number concentration (cm^{-3}), N_i is the measured number concentration (cm^{-3}), Q_{det} is the volumetric flow rate through the detector, which is 6 cc/sec, and τ_{det} is the residence time of particles in the optical scattering volume (0.5 μsec). The coincidence correction from Equation 2 for the aMCPC at various concentrations was included in Table 6.1 from the manufacturer's manual.

10.0 Setup and Operation of Instrument

Deployment on the TigerShark or ArcticShark

The ACCESS aMCPC is installed on the multiple instrument stackable tower (MIST) in the main payload bay of the ArcticShark unmanned aerial system (UAS). The MIST itself is seated in the payload bay connected by four vibration isolators to reduce noise. Outside air is brought into the payload via a universal inlet installed on the nose of the UAS. The inlet is pumped actively via a scroll pump and controlled with a mass flow controller. The instrument is initialized by an onboard data acquisition system that operates the Brechtel LabView software. The data is transmitted to scientists on the ground in real time.

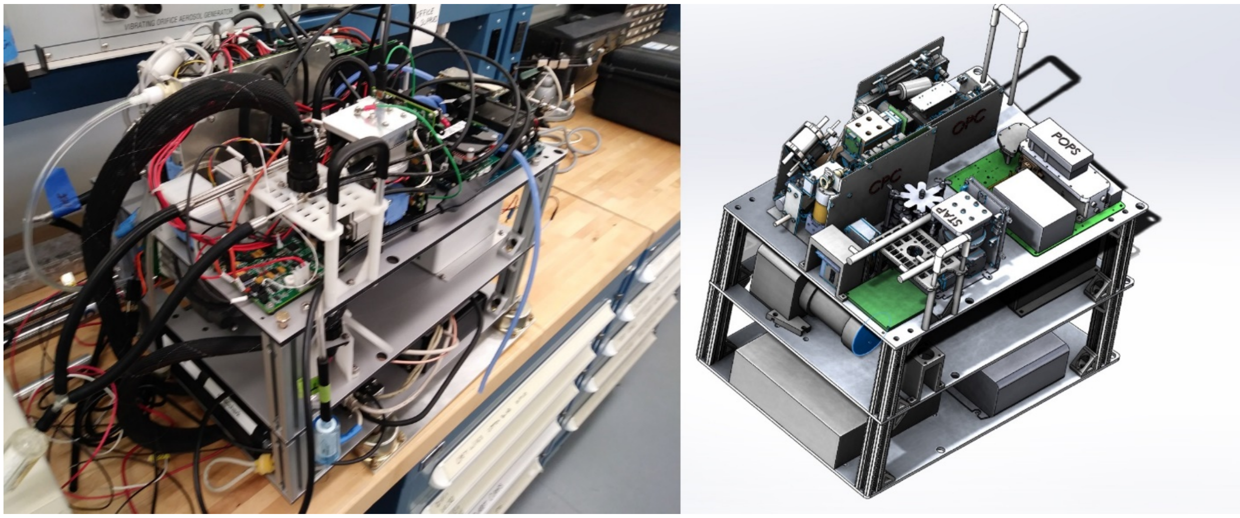

Figure 6. MIST instrument payload tower. Left: On laboratory bench. Right: Schematic with instrument placement clarified.

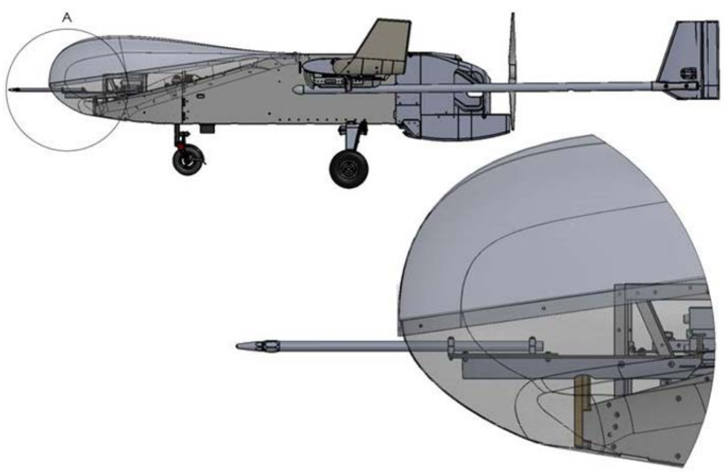

Figure 7. ArcticShark with nose inlet installed.

General Setup

1. Remove protective caps and covers.
2. Connect the butanol bottle tubing to the filling port.
3. Note the filling bottle should be removed before flight.
4. Ensure that the sample tubing and exhaust tubing are adequately connected.
5. Apply power.
6. Initialize software via data acquisition (DAQ).

The butanol consumption of the aMCPC is about 320 ml per week when operated 24 hours per day, seven days a week.

11.0 Software

For further details, consult the manufacturer's manual.

12.0 Calibration

Calibration activities include verifying the 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).

13.0 Maintenance

The following maintenance procedures are required:

- Refill the butanol reservoir before each flight.
- Drain butanol from the butanol reservoir before 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 0.36 lpm, with a variability of ±5%.
- Correct flooded optics whenever there is an indication that flooding has occurred.
- “zero” count checking. Connect a HEPA filter to the inlet, and the total number concentration should drop to zero in several seconds.

Refer to the manufacturer's manual and the ACCESS preventive and maintenance procedure for each maintenance action's detailed procedures.

14.0 Safety

The CPC is a Class I laser-based instrument. During regular 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

Advanced Mixing Condensation Particle Counter Model 9403. https://www.brechtel.com/products-item/particle-condenser/. Accessed 08/31/2020.

Bates, TS, PK Quinn, JE Johnson, A Corless, FJ Brechtel, SE Stalin, C Meinig, and J Burkhart. 2013. “Measurements of atmospheric aerosol vertical distributions above Svalbard, Norway using unmanned aerial systems (UAS).” *Atmospheric Measurement Techniques* 6(8): 2115−2120, https://doi:10.5194/amt-6-2115-2013

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(a6): 674–682, https://doi.org/10.1016/j.jaerosci.2007.05.001

Mordas, G, H Manninen, T Petäjä, P Aalto, K Hämeri, and M Kulmala. 2008. "On operation of the ultrafine 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(2): 152–158, https://doi.org/10.1080/02786820701846252

Ahn, KH, and BYH Liu. 1990. "Particle activation and droplet growth processes in condensation nucleus counter I. Theoretical background." *Journal of Aerosol Science* 21(2): 249–261, https://doi.org/10.1016/0021-8502(90)90008-L

Stolzenburg, MR, and PH McMurry. 1991. "An ultrafine aerosol condensation nucleus counter." *Aerosol Science and Technology* 14(1): 48–65, https://doi.org/10.1080/02786829108959470

Wang, J, V Faye McNeill, DR Collins, and RC Flagan. 2002. "Fast Mixing Condensation Nucleus Counter: Application to Rapid Scanning Differential Mobility Analyzer Measurements." *Aerosol Science and Technology* 36(6): 678−689, https://doi.org/10.1080/02786820290038366

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science