Condensation Particle Counter Fundamentals

Factors to Consider when Selecting a CPC for your Application

Application Note CPC-002 (A4)

Overview

Condensation Particle Counters (CPCs) enable real-time particle number (PN) concentration measurements of airborne particles down to one (1) nanometer in diameter. These instruments measure discretely nearly 100% of the particles in the sample flow, and as a result have a high degree of accuracy. TSI® has been designing research-quality CPCs for over 40 years, and has the engineering and manufacturing experience to deliver instrumentation which produces data that is accurate, precise, and repeatable. The result is a comprehensive line of 10 state-of-the-art CPC models. Each CPC has a unique set of features, to ensure one is available to suit every application.

Table 1: CPC Specification Comparison

	3007	3750 & 375010[1]	3752		3756		3757-50	3783		3789		3790A & 3790A-10[7]
Specifications												
D_{50} Min. Size (nm)	10	7(10)[1]	4		2.5		1[3]	7		2.2, 7, custom [5]		23 (10[7])
Max. Concentration (particles/cm^3)	100,000	100,000	100,000; up to 10^7 [2]		300,000		300,000	1,000,000		200,000		10,000 (50,000)[8]
Concentration Accuracy (%)	±20	±5	±5; ±20[2]		±10		±10; ±15[4]	±20		±5		±10
Sample Flow (LPM)	0.1	1.0	0.3		0.05		0.15[9]	0.12		0.3		1.0
Total Inlet Flow Mode (LPM)	0.7	1.0	0.3	1.5	0.3	1.5	2.5	0.6	3.0	0.6	0.6, 1.5, or 2.5[6]	3.0
Response – T95 (s)	<~3	~2	<4	<3	<3	<1	1.9	<5	<3	<1		<5
Response – T10–T90 (s)	<2	<1	<2	<1.5	<2	<0.2	1.5	<2		0.6		<3

(continued on next page)

Specifications	3007	3750 & 375010[1]	3752	3756	3757-50	3783	3789	3790A & 3790A-10[7]
								
Flow Source	Internal	External	Internal	Internal	External	External	Internal	External
Working Fluid	Isopropanol	Butanol			DEG + Butanol	Water		Butanol
Weight	1.7 kg	6.6 kg (~14.6 lbs)	9.1 kg (~20 lbs)	9.1 kg (~20 lbs)	<20 kg (<44 lbs)	~10 kg (~22 lbs)	8.2 kg (18.2 lbs)	5.5 kg (12 lbs)
Display	Digital LCD	Embedded touch-display				Embedded touch-display		Digital LCD
Data Logging/ Storage	Internal memory	Internal memory				Flash drive	Internal memory	SD/MMC flash card
Software Compatibility[10]	Aerosol Instrument Manager™ 9 software and Aerosol Instrument Manager™ 10 software	Aerosol Instrument Manager™ 11 CPC software	Aerosol Instrument Manager 11 CPC software	Aerosol Instrument Manager 11 CPC software	Aerosol Instrument Manager 11 CPC software	Aerosol Instrument Manager 9 software and Aerosol Instrument Manager 10 software	Aerosol Instrument Manager 11 CPC software	Aerosol Instrument Manager 9 software and Aerosol Instrument Manager 10 software
TSI® SMPS™ Compatibility	No	Yes (3082)[11]			Yes (3082)[11,12]	No	Yes (3082)[13]	No
Pulse height monitor	No	Yes				Yes	Yes	Yes
Raw data time resolution (Hz)	1	50				10	50	10
Extras	Battery-powered operation	On-board data acquisition with remote access and control Fully operable through Ethernet connection				Water use ~ 250 mL/wk.	(same as 3750-series)	90% counting eff. at 41nm (15 nm [7])

T95: Rise time from 0 to 95% or decrease from 95% to zero (fall time). TSI's traditional approach
T10/90: Rise 10% to 90%, fall 90% to 10%

[1] The 375010 receives a CEN-compliant 10 nm calibration.
[2] 3752: Above 100,000 particles/cm^3 the 3752 uses photometric mode which has concentration accuracy of ±20%.
[3] 1.4 nm electrical mobility diameter, 1.1 nm geometric diameter. Verified with NaCl particles.
[4] 3757-50: ± 10% below 1.65 × 10^5 particles/cm^3; ± 15% at 3 × 10^5 particles/cm^3.
[5] D50 is user-selectable from the control panel.
[6] Requires orifice change.
[7] The 3790A-10 is available by applying a 10-nm D50 calibration to the 3790A.
[8] The 3790A-10 also expands the maximum concentration range to 50,000 particles/cm^3 by way of increasing the linearity allowance from 10% to 20%.
[9] The capillary flow rate in the 3757 is 0.15 LPM and the sample flow rate in the 3750 mounted on top is 1 LPM.
[10] Aerosol Instrument Manager™ 9 software for CPC/EAD version or Aerosol Instrument Manager™ 9 software "all" version; Aerosol Instrument Manager™ 10 software "all" version; Aerosol Instrument Manager 11 CPC software version.
[11] When used in an SMPS™ system, works with Aerosol Instrument Manager 10 software "all" version or Aerosol Instrument Manager 11 SMPS™ software.
[12] Only works with Aerosol Instrument Manager 10 software or Aerosol Instrument Manager 11 SMPS™ software (standalone SMPS™ operation from 3082 classifier is not possible).
[13] When used in an SMPS™ system, only works with Aerosol Instrument Manager 11 SMPS™ software.

Condensation Particle Counter Theory

In a condensation particle counter, particles that are too small to scatter enough light to be detected by conventional optics are grown to a larger size by condensation. A vapor, which is produced by the instrument's "working fluid" is condensed onto the particles to make them larger. After achieving condensational growth, CPCs function similar to optical particle counters in that the individual droplets then pass through the focal point of a laser beam, producing a flash of light. Each light flash is counted as one particle. The science of condensation particle counters, and the complexity of the instrumentation, lies with the technique to condense vapor onto the particles. When the vapor surrounding the particles reaches a specific degree of supersaturation, the vapor begins to condense on the particles. The magnitude of supersaturation determines the minimum detectable particle of the CPC. In an ideal CPC, the supersaturation profile within the instrument is tightly controlled.

Continuous Flow CPCs

While there are several methods which can be used to create condensational growth, the most widely used technique is a continuous, laminar flow method. Continuous flow laminar CPCs have more precise temperature control than other types of CPCs, and they have fewer particle losses than instruments which use turbulent (mixing) flow. In a laminar flow CPC, a sample is drawn continuously through a conditioner region which is saturated with vapor and the sample is brought to thermal equilibrium. Next, the sample is pulled into a region where condensation occurs. In an alcohol based CPC (isopropanol or butanol), the conditioner region is at a warm temperature, and the condensation region (saturator) is cooler. Water has very high vapor diffusivity, so a laminar flow water-based CPC with a cool condensation region does not work thermodynamically. In a laminar flow water-based condensation particle counter (WCPC), the conditioner region is cool, and the condensation region is hot (growth tube). The condensational growth mechanism in a WCPC is similar to the situation which occurs when your glasses fog over when coming inside on a cold day. See the DIN VDI 3867 standard for more details.

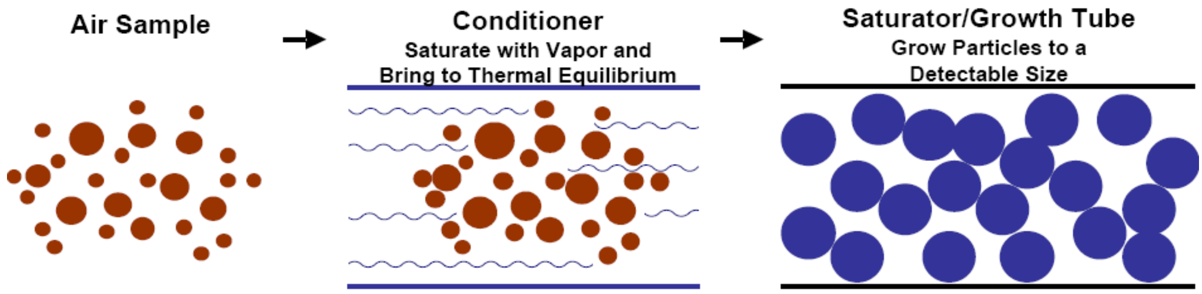

Figure 1: Continuous, laminar flow condensation particle counter (CPC) operation.

Condensation Particle Counter (CPC) Selection Criteria

There are several primary variables that should be considered when selecting the optimum CPC for various applications.

- **Working Fluid**—TSI® is unique in that we offer a choice in the working fluid used to create the condensational particle growth needed to detect the smallest nanoparticles. Some applications may require the use of one working fluid over the others, while the working fluid may not be a deciding factor for other applications.
  - **Isopropyl alcohol (isopropanol)** is used in the 3007 Handheld CPC, Nanoparticle Emissions Tester (NPET and NPET-HC), and NanoScan SMPS™ system, Isopropanol provides excellent condensational growth, is easy to procure and is a relatively benign chemical. This is a convenient working fluid for hand-held instruments designed primarily for point source identification. Laminar flow CPCs designed to work with alcohols do not function when water is used as the working fluid. However, water readily diffuses into isopropanol (IPA). If too much water from the atmosphere dissolves into the IPA, the CPC will no longer accurately count particles. Therefore, isopropanol is not a good choice in instruments that are designed to run for long periods of time, or that have large liquid reservoirs.

- **n-Butyl alcohol (butanol)** is the working fluid that has been used most in the history of commercial CPCs. Butanol is a large molecule that has low vapor diffusivity, so it stays in the vapor stream to provide reliable, repeatable condensation in CPCs. Additionally, water has more limited solubility in butanol compared isopropanol—making it a better choice for long term applications. Because of these two primary advantages, most of the historical aerosol science data has been taken using butanol CPCs. However, butanol also has a couple of disadvantages. Butanol vapor is a VOC with a strong odor. Beside the odor, this can be problematic if other gas analyzers are being used near butanol CPCs, or if human exposure is a concern. Butanol also needs to be procured from a chemical manufacturer, and a supply must be stocked for use in the CPC.

- **Diethylene Glycol (DEG)** is used exclusively in the 3757 Nano Enhancer and the 3757-50 1 nm CPC. The DEG enables the 3757 to act as a "growth activator" for the smallest particles (down to 1 nm). DEG has a propensity to avoid homogenous nucleation, has high surface tension, relatively low toxicity, and low cost. It is fairly hygroscopic, so measures must be taken to prevent water uptake from high relative humidity. The high surface tension of the DEG, limits the growth of the particles to approximately 100 nm. For this reason, it must be paired with a true CPC (such as the 3750) in order to finish the growth process and count the particles.

- **Distilled Water (<6ppm) or Type III Water**—Water-based CPCs have a clear set of advantages. Water is non-toxic, environmentally friendly and easy to procure. Additionally, in the atmosphere, water vapor plays a significant role in the size of atmospheric particles, so in general it seems logical to mimic this occurrence to measure the concentration of sub-micron particles that may play a role in visibility and climate change issues. Water, however, also has a few disadvantages. Water is an excellent solvent, so it can readily pick up impurities. To counteract this, distilled or Type III water needs to be used in the WCPCs (not tap water), it can allow microbial growth if the CPC is not drained before long-term storage, and the wicks needs to be replaced after approximately 6 months of continuous operation. Additionally, if particles of an extremely pure hydrophobic material (i.e., lab generated oil or other substance) are sampled with a WCPC, the minimum detectable particle diameter of the instrument may be increased. All working fluids have some type of slight material dependency to various degrees. In general, naturally occurring aerosols do not pose a counting efficiency problem for either alcohol based (butanol) or water-based CPCs.

- **Minimum Detectable Particle Size**—The minimum detectable particle diameter of a CPC can be described with a detection efficiency curve where the CPC counting efficiency versus a standard is plotted as a function of particle diameter (Figure 2). A steeper curve is generally preferred, so the counting range of the CPC can be more precisely defined. The minimum detectable particle size is commonly defined as the diameter at which 50% of the particles are detected by the counter (D_{50}). Typically, a lower detectable particle size is associated with a more complex instrument. The primary factors affecting the D_{50} are:

  - The temperature differential between the conditioner and saturator/growth tube (initiator). The higher the temperature differential between the conditioner and saturator/growth tube (initiator), the lower the D_{50}.

  - The aerosol sample flow scheme: if a sheath flow is used in the CPC, the detection efficiency curve will be typically steeper. When growing the particles in the condenser chamber, the highest saturation ratio occurs on the centerline of the flow stream at some distance down the condensing tube. When using sheath air, the CPC confines the aerosol to the centerline of the condenser tube where level of supersaturation is the highest, resulting in high detection efficiency for small particles.

  - The physical design of the CPC engine (conditioner, saturator/growth tube (initiator), optics). The dimensions of the condensation region and the sensitivity of the optics & electronics also affect the minimum detectable particle size.

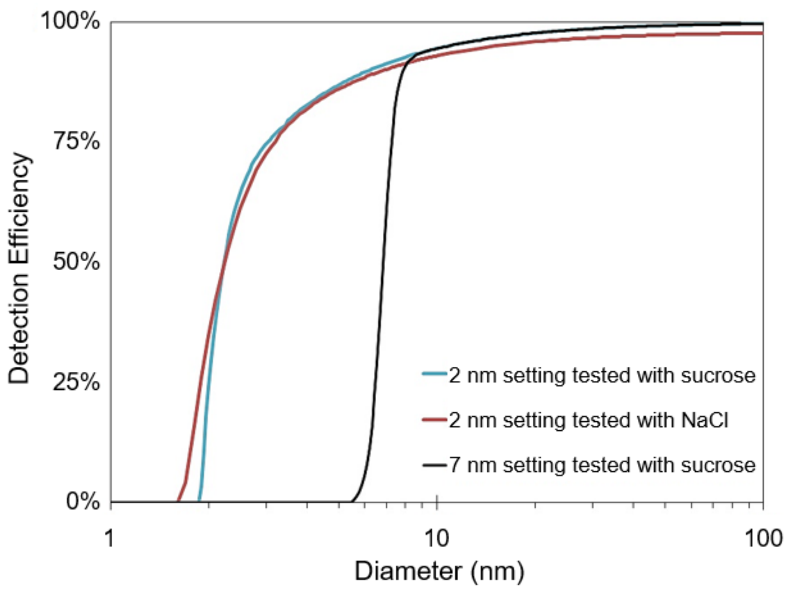

Figure 2: CPC Model 3789 counting efficiency curves using a variety of monodisperse aerosols and an electrometer as the reference detector.

NOTICE
CPCs are designed to effectively count the smallest of nanoparticles. The maximum detectable size of a CPC is generally anywhere from 1 to 3 µm. Particles larger than about 1 micron are very easily lost due to inertial impaction, (nanoparticles are essentially unaffected by this loss mechanism). These supermicron sized particles cannot penetrate through the CPC flow path to the detection region. If a sharp upper size limit is important for you application, it is best to consider using a low pressure drop inlet cyclone on your instrument.

- **Concentration Range**—TSI® CPCs have the widest single particle counting concentration range of any commercially available CPCs. This is achieved primarily by state-of-the-art electronics processing featuring live-time coincidence detection design, and by carefully designed optics which result in high signal to noise ratios. Additionally, in the WCPCs, the condensation region has been optimized to kinetically limit growth—thereby reducing final droplet size variation as a function of concentration. Another consideration regarding the concentration range of CPCs is that in general the sample flow rate has an inverse relationship with the maximum concentration specification. The higher the sample flow rate, the lower the maximum concentration value. Finally, it is important to note that the 3752 uses a photometric mode which enables it to measure particle concentrations up to 10^7 particles/cm^3. This technique is a departure from single particle counting and has been used widely to extend CPC concentration ranges.
- **Concentration Accuracy**—Concentration accuracy in a single particle counting CPC is determined primarily by the flow control and the detection mode. Optical alignment can also affect concentration accuracy, but the optical alignment in TSI® CPCs is very tightly controlled, and does not in general affect concentration accuracy. When the CPC is used in single particle counting mode, the concentration accuracy is primarily based on the flow control accuracy. For most instruments, the flow control will beat the standard ± 10% specification, so concentration accuracy will be less variable. The photometric mode used in the 3752 is fundamentally less accurate than single particle counting, with an accuracy specification of ±20%.
- **SMPS™ Compatibility**—Whether or not the CPC can be used as a component of a Scanning Mobility Particle Sizer™ (SMPS™) Spectrometer sizing system is also an important consideration in the selection process of a CPC. The SMPS™ technique combines a size selecting device called a Differential Mobility Analyzer (DMA) with a CPC and scans the sample aerosol to get a high-resolution size distribution in the range from 1 nm to 1000 nm.

- **Sample Flow**—For many applications, the sample flow is a useful selection criterion. Higher sample flow rates result in better counting statistics. It should be considered that sheathed instruments, while fundamentally having a lower sample flow, also have a lower D_{50} and steeper detection efficiency curve. Additionally, as mentioned above, CPCs with lower sample flow rates invariably have higher concentration ranges.
- **Inlet Flow**—Higher flow rates result in less sampling diffusion losses. In general higher inlet flow rates are beneficial unless the application does not allow for it. Selectable flow rates are useful for SMPS™ component systems, where the flow rate of the CPC has some effect on the size range of the instrument.
- **Flow Source**—For some applications, the convenience of an instrument with an internal vacuum pump is attractive. However, for other applications, the robustness of a large external pump may be preferred.
- **Response Time**—TSI® Incorporated's laminar flow CPCs have extremely fast response times. In fact, the 3789 Versatile Water-based CPC (V-WCPC) is one of the fastest CPCs in the world. Faster response times are useful for measuring particle nucleation/formation/transformation events or to measure short lived nanoparticle emission bursts. Fast CPCs also make fast SMPS™ sizing measurements possible.
- **Compliance with Standards**—Some research communities are subject to standards that describe exactly how certain measurements are to be made (e.g., engine exhaust particle emissions). These standards can even dictate parameters on an instrument itself. If you are doing measurements that must follow a standard, be sure to read and understand the requirements of the standard. Your TSI® sales representative can help you decide which CPC will enable you to accomplish your measurement goals while still being compliant with your standards. The following standards are relevant to TSI® CPCs:
  - CEN/TS16976: This technical specification pertains to measuring the number concentration of particles in ambient air. It specifies that a CPC must be used. It also specifies the working fluid and numerous other aspects of the CPC and its calibration. From the TSI portfolio, Model 3750-CEN is compliant with the requirements of CEN/TS 16976.
  - ISO 27891: This standard describes how to calibrate CPCs. TSI does offer a CPC service—for the model 3750 CPC—that is compliant with the requirements of ISO 27891.
  - ISO 17025: This standard pertains to calibration processes in general, and is not specific to CPCs in any way. Several TSI products have calibration procedures that are compliant with ISO 17025, including the Engine Exhaust Condensation Particle Counters.

TSI Condensation Particle Counters

Table 3 lists the model number, name, and brief description of the CPCs offered by TSI® Incorporated.

Table 3: CPC Model Names and Descriptions

Model #	Instrument Name	Description
3007	Handheld Particle Counter	A battery powered, portable instrument. The 3007 measures down to 10 nm and has a flow control feedback loop for greater concentration accuracy.
3750 & 375010	Condensation Particle Counters	A compact, full-featured butanol CPC that detects down to 7 nm with an inlet flow of 1 LPM. The 3750 is rugged and proven to be reliable in a variety of applications. The 3750 can be ordered with a CEN-compliant calibration (375010) for applications that require such, including ISO 27891.
3752	Condensation Particle Counter	A general purposed CPC that detects particles down to 4 nm at concentrations up to 10^7 particles/cm^3. The 3752 is the instrument of choice for high concentration applications.
3756	Ultrafine Condensation Particle Counter	A favorite for researchers investigating the smallest nanoparticles, this state-of-the-art CPC detects particles down to 2.5 nm with single particle counting up to 300,000 particles/cm^3.
3757-50	1 nm CPC	Includes the 3757 Nano Enhancer and the 3750 CPC. Similar to a CPC, but without the particle counting optics, the 3757 is used to pre-grow the smallest particles (down to 1 nm) to a size detectable by the 3750. For nucleation studies, the 3757-50 is a must-have accessory stand-alone or in combination with the SMPS™ system.
3783	Environmental Particle Counter™ (EPC™) Monitor	This water-based CPC was designed specifically for long-term ultra-fine particle monitoring applications. The EPC™ Monitor is rack-mountable, has been tested extensively on outdoor air, and can measure concentrations up to 1,000,000 particles/cm^3 using exclusively single particle counting.
3789	Versatile Water-based Condensation Particle Counter (V-WCPC)	This cutting-edge counter can measure down to 2.2 nm. The 3789 features an adjustable D50, making it the most versatile of the CPCs in TSI® Incorporated's lineup.
3790A & 3790A-10	Engine Exhaust Condensation Particle Counters (EECPC)	The 3790A is used to accurately measure PN concentration of exhaust emissions. The EECPC is fully compliant for light-duty vehicle certification in accordance with UN-ECE Regulation 83 when used with a compliant dilution system, and was used as the benchmark instrument for this regulation. The 3790A can also be specified for applications that require a D50 of 10 nm (3790A-10).

Condensation Particle Counters for Common Applications

The instrument application and desired measurement outcomes will factor largely into the decision of which CPC model to use. In general, some CPCs are more suited to particular applications than others. However, most users have specific practical needs within applications that should be identified and addressed. Table 4 can be used as a guide for beginning the search for your CPC. The best approach is to begin a conversation about your unique application with one of TSI® Incorporated's experienced sales managers. Visit www.tsi.com for more information on how to reach your TSI® sales representative.

Table 4: CPC Application Selection Guide

For best results, contact a TSI® representative for help with CPC model selection.

	3007	3750 & 375010	3752	3756	3757-50	3783	3789	3790A & 3790A-10
Indoor Air Quality	X							
Industrial Hygiene	X							
Point Source Identification	X							
Outdoor Monitoring		X				X		
Particle Nucleation Research			X	X	X			
Combustion / Emission Research		X	X	X	X			X
Nanotechnology		X	X	X	X		X	
Inhalation Toxicology		X						
Instrument Verification / Calibration		X		X				
Filter Testing		X						
Basic Aerosol Research		X	X	X	X		X	X

Commonly Used Abbreviations

Acronym	Description
CPC	Condensation Particle Counter
DEG	Diethylene Glycol
DMA	Differential Mobility Analyzer
EPC	Environmental Particle Counter
HPLC	High Performance Liquid Chromatography
IPA	Isopropyl Alcohol (Isopropanol)
LCD	Liquid Crystal Display
PN	Particle Number
SMPS™	Scanning Mobility Particle Sizer™ Spectrometer
WCPC	Water-based Condensation Particle Counter

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TSI Incorporated – Visit our website www.tsi.com for more information.

USA **Tel:** +1 800 680 1220
UK **Tel:** +44 149 4 459200
France **Tel:** +33 1 41 19 21 99
Germany **Tel:** +49 241 523030
India **Tel:** +91 80 67877200
China **Tel:** +86 10 8219 7688
Singapore **Tel:** +65 6595 6388

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