TSI® INSTRUMENTATION FOR MEASURING ATMOSPHERIC PARTICLES ACCORDING TO CEN/TS 16976:2016 AND 17434:2020

A BUYER'S GUIDE TO CEN COMPLIANCE (A4)

Contents

Introduction

While air quality varies significantly around the globe, there is also variation in how air quality is measured. Specifically within atmospheric aerosol measurement, the two most widely-used quantification approaches are measuring particle mass (PM) and particle number (PN). While US and other regulations are based on particle mass, there is a growing movement towards also quantifying particle number.

While number-based measurements of atmospheric aerosol have been made for years in numerous countries, it has been difficult to meaningfully compare data gathered internationally. This difficulty is due to the fact that particle measuring sites were sometimes using different sampling, conditioning, and particle measurement instrumentation. "Harmonizing" these aspects is key to comparing data and drawing conclusions relevant to all the fields relevant to ambient aerosols, including emissions regulations, public health, and climate.

Basics of the CEN/TS Standards for Atmospheric Monitoring

The overall goal of the CEN/TS[1] standards pertinent to atmospheric monitoring is to “harmonize” the measurements taken. That means that in order for atmospheric monitoring data to be compliant with the relevant CEN/TS standards, that data must be collected using compliant sampling, conditioning, and particle measurement instrumentation. These standards specify what instrumentation must be used, what features an instrument must have and/or criteria it must fulfill, as well as how data must be reported.

CEN/TS 16976

CEN/TS 16976 "Ambient air - Determination of the particle number concentration of atmospheric aerosol” pertains to measurements of particle number concentration and was published in 2016.

CEN/TS 17434

While CEN/TS 16976 pertains to particle number, CEN/TS 17434 “Ambient air - Determination of the particle number size distribution of atmospheric aerosol using a Mobility Particle Size Spectrometer (MPSS)” pertains to particle size distribution. The most recent finalized revision of the standard was released in 2020.

Anticipated Changes to the CEN Standards

As of 2021, CEN/TS 16976 is undergoing revision, and is in the process to become a European Standard. Several specifications are under discussion for modification. Topics that are under discussion for revision include:

- Resolving some inherent contradictions between the 16976 and 17434 standards on some specific requirements.
- Changing the D50 requirement for the CPC from 7 nm to 10 nm.
- Limiting the potential cutpoint of a pre-separator cyclone to only PM2.5.

These topics are pertinent to system requirements as detailed below in Tables 2, 5, 6, 10 and 14. Please see those tables, and the text that follows each of them, for more information.

Relevance of these two CEN Standards

These two CEN standards are relevant to any governmental, private or academic institution which intends to measure ultrafine and fine particles in ambient air. While some may consider to follow those standards only partially, the comparability, traceability and acknowledgment of the results is established by these harmonized procedures. Adhering to the prescribed measurements is securing the reputation of the air quality assessment.

[1] CEN stands for European Committee for Standardization. CEN is an association – officially recognized by the European Union and by the European Free Trade Association – that brings together the National Standardization Bodies of 33 European countries. CEN is committed to develop European Standards for various kinds of proucts, materials, services, and processes. TS stands for Technical Specification. A Technical Specification is a normative document that is established by an appropriate technical body within CEN. All Technical Specifications are approvied through a vote by CEN national members.

Structure of this Buyer's Guide to CEN Compliance

This Buyer's Guide is divded into five sections. Each section is devoted to a main function within atmospheric aerosol monitoring: sampling and drying, dilution, humidity measurement, particle number concentration measurement, and particle size distribution measurement.

Within each section, this Guide uses tables to detail the requirements that the two CEN standards (CEN/TS 16976:2016 and 17434:2020) specify for instrumentation. When applicable, details pertaining to specific line items within a table may be found in the text following that table.

Following the requirements, a subsection titled "The TSI® Solution" is devoted to the relevant TSI® instrument to demonstrate how instrument meets the listed requirements. At the end, a final section titled "The Full TSI® Solution" provides a complete overview and demonstrates compliance of all components.

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Section 1: Sampling and Drying

Any measurement can only be as representative as the sample that has been taken for analysis. As is the case with any other scientific endeavor, care must be taken to ensure that the aerosol sample delivered to the particle instrument is representative of the aerosol one wishes to characterize. Specifically, the sampling and conditioning process should aim to preserve the size distribution and concentration of the sampled aerosol as much as possible. Condensation of water from the humid ambient air that is sampled is affecting the measurement results and can harm even the instruments.

A CEN-compliant sampling system includes several components: a PM10 sampling head, a sampling tube, a cyclone, and a dryer. Use of the cyclone is optional, and depends upon the size distribution of the aerosol to be sampled. Design and performance requirements are covered in the following tables.

Dilution is optional; a diluter should only be used under certain conditions as specified by CEN/TS 16976:2016 Section 5.1.3 (see Table 4 line item #1). Design and performance requirements for the diluter are covered in "Section 2: Dilution (optional)" within this document.

Within Tables 1, 2, and 3 several line items refer to both CEN/TS 16976:2016 and 17434:2020. In such cases, where a quote of the standard is presented, the quote is taken from CEN/TS 16976:2016.

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Sampling: Design Requirements

Table 1: Design requirements for the sampling inlet (not including the dryer).

Line item	Design aspects		Section: 16976	Section: 17434	CEN requirement
1	Overall system		7.1	8.1	• The sampling system must bring a sample of ambient air from the outdoors to the inside of the monitoring station while preserving the size distribution of the ultrafine particles in that air. • The sampling system must condition the aerosol to defined relative humidity and temperature.
2	Sampling head	Design	5.1.1	6.1.1	• The sampling system's design must permit that the sampling process results in representative sampling, even under a wide range of wind conditions.
3		Cutpoint			• Because ambient air can contain micrometer-scale particles, an inlet that removes such particles must be used; PM10 and PM2.5 inlets are permitted.
4	Pre-separator			7.1	• A pre-separator should be used if the aerosol to be measured includes a nontrivial amount of particles larger than can be measured by the particle sizer. • The pre-separator can be an impactor or cyclone, and may be included either in the particle sizing instrument or in the sampling system.
5	Sample tube	Vertical	5.1.1	6.1.1	• The primary sampling tube should ideally be entirely vertical.
6		Gas sampling			• Particle sampling should be conducted independent from gas sampling.
7		Isoaxial sampling			• The sampling system must draw in a much larger flow rate of air than is required by the particle measurement instruments. The purpose of this larger primary flow is to reduce losses of particles due to diffusion. • The secondary flow – the portion of this primary flow that will go to the instrument(s) – should be sampled isoaxially (i.e. in a centered fashion) from the primary flow, and this sampling tube must be kept short.
8		Laminar flow			• Within the primary sampling tube, the air flow should be laminar, in order to reduce particle loss due to turbulence within the sampling tube.
9	**Materials**	Sampling lines	5.1.1		• The sampling system should be manufactured from a material that is conductive and corrosion-resistant. It must have a smooth surface and be electrically grounded.
10		Flexible tubing		6.1.1	• Conductive flexible tubing may be used for connecting the sampling system to instrumentation, but the lengths of such tubing must be kept short (i.e. <50 cm).

The pre-separator (line item #4) is optional; if used, it may be housed in either the sampling system or within the MPSS. Refer to Table 13 line item #1.

Sampling: Performance Requirements

Table 2: Performance requirements for the sampling inlet (not including the dryer).

Line item	Performance aspects	Section:		CEN requirement	
		16976	17434		
1	Diffusion losses	5.1.1		• Diffusion losses within the sampling system must be <30% for 7 nm particles.	
2			6.1.1	• Diffusional losses of particles within the sampling system must be determined, and the particle data must be corrected for those losses.	
3			8.3	• When determining diffusion losses of particles, theoretical calculations may be used for simple geometries. For more complex geometries, either an experimental investigation of losses, or published peer-reviewed data, may be used.	
4	Laminarity	7.6		• Whether flow in the primary sampling tube is laminar or not can be determined by measuring the primary sampling flow, and using that measurement along with tube geometry to calculate the Reynold's number. The flow meter used to measure the primary flow must have an accuracy better than…	5%
5			8.6		2%

The equivalent length of the sampling system (and thus diffusional losses within the system – see line item #3) depends upon the components used and the lengths of those components. Some aspects of the sampling system will necessarily vary from location to location – specifically, the length of the sampling tube, the optional inclusion of cyclone (and if included, which cutpoint of cyclone).

The resolution of the discrepancy regarding the flow meter accuracy (line items #4–5) is subject to revisions by the CEN committees. TSI® flow meters fulfill the stricter accuracy of ±2%.

Drying: Design and Performance Requirements

It is critical that the aerosol is dried sufficiently (and repeatably across sites) prior to measurement. This has several benefits. First, it ensures the accuracy of size measurements even when particles are prone to growing under humid conditions due to their chemical composition (hygroscopicity). Second, it permits intercomparisons of size measurements between sites since hygroscopic growth is no longer a complicating factor. Finally, drying the sample flow (as well as the particles contained within that flow) protects the instruments from condensation, thus protecting their performance and prolonging their maintenance interval.

Table 3: Design and performance requirements for the drying system included in the sampling inlet.

Line item	Design aspects	Section: 16976	Section: 17434	CEN requirement
1	Influence of ambient conditions on drying setup	5.1.2	6.1.2	• Whether drying is necessary depends upon ambient conditions. The CEN standards specify the following three scenarios: o For warm and very dry environments, no aerosol dryer is needed. o For moderately humid environments, the secondary flow must be dried. o For environments that are humid enough that the primary sampling flow may experience condensation upon being cooled to the temperature of the environmentally-controlled monitoring station, the primary flow must dried. The secondary flow may require additional drying.
2	Drying method	5.1.2	6.1.2	• Any of three mehods may be used to dry the aerosol: silica-based diffusion dryer; membrane dryer; dilution with dry air.
3	Permissable humidity at CPC inlet	7.4		• Sample drying must achieve a relative humidity, as measured at the instrument inlet, below 40% relative humidity (%RH). The humidity sensor must have an accuracy of 3%, and the sample humidity requirement of 40% must take into account the maximum error of the humidity measurement device.

The TSI® Solution: Sampling System for Atmospheric Particles 3750200

The Sampling System for Atmospheric Particles from TSI® samples and conditions atmospheric aerosol in compliance with the requirements of CEN/TS 16976:2019 and 17434:2020 as detailed in Tables 1, 2, and 3.

Figure 1. Sampling System for Atmospheric Particles Model 3750200.

The sampling system is designed specifically for aerosol sampling (Table 1 line item #6) and delivers a representative sample of atmospheric aerosol to the particle measurement instruments attached to its outlet. Standard components – including a PM10 sampling head and optional PM2.5 cyclone – bring in the sample from outside with a high, laminar primary flow (16.67 L/min). With a maximum secondary flow (dried aerosol flow) of 4 L/min, the sampling system easily permits the use of several particle instruments simultaneously for continuous monitoring. Additional particle instrumentation for temporary comparison purposes can also be connected.

The dryer used in the Sampling System is a membrane (Nafion) dryer (Table 3 line item #2), and it achieves a relative humidity of <40% when a sufficient pump is used (Table 3 line item #3). For locations that may experience dewpoints above 25°C, the sampling system can be configured with a pump which supplies a deeper vacuum to enhance dryer performance. For further details on the pumps, refer to the Solutions Brochure (US) and (A4).

The final relative humidity of the sample flow is measured using the Relative Humidity and Temperature Sensor RHT3000, covered in Section 3. This sensor is compatible with both the particle counter and particle sizer; whichever instrument it is connected to (via USB cable) will record the sample humidity alongside particle data.

Diffusion losses in the sampling system are approximately 27% for 7 nm particles (Table 2 line item #1), assuming a primary sampling tube length of 1.5 m. Effective lengths for all sampling system components have been determined (Table 2 line items #2–3).

The optional dilution aspect of the sampling is described in Section 2.

Section 2: Dilution (optional)

Aerosol number concentrations can vary widely by location. Some locations have both a high particle concentration and a high potential to impact human well-being; for example, traffic junctions, airports, or seaports. In such settings, the very characteristic that makes it desirable to measure ambient particles – their high concentration – makes it difficult to do so. Diluting the aerosol sample prior to measurement can solve this problem.

From the perspective of CEN/TS 16976:2016 and 17434:2020, dilution is optional, and should only be used when local concentrations exceed that which the CPC can handle in single particle mode. Please refer to Table 4 line item #1, and Section 5.1.3 of 16976.

Table 4: Design and performance requirements of the (optional) dilution system.

Line item	Design or Performance aspects	Section: 16976	Section: 17434	CEN requirement	
1	Particle-free air	5.1.3		• When it is not possible for the CPC at a given site to accurately measure the particle concentrations without using photometric mode, the sample must be diluted using particle-free air.	
2	Dilution factor accuracy	7.2		• If dilution is used, the dilution factor must be stable with time, and it must be accurate within…	5%
3			8.2		6.5%

The stability of the dilution factor (line items 7–8) is required to be ±5% according to CEN/TS 16976, but ±6.5% according to CEN/TS 17434. The resolution of the discrepancy is subject to revisions by the CEN committees. As described below, TSI® Incorporated's Aerosol Diluter Model 3333-10 controls the dilution factor within the tighter limit of ±5%.

The TSI® Solution: Aerosol Diluter Model 3333-10

Some atmospheric monitoring locations occasionally experience particle number concentrations higher than 100,000 particles/cm^3. In such cases, use of a diluter will keep the number concentration within the measurement range of the CPC. The Aerosol Diluter Model 3333-10 dilutes the sampled aerosol in compliance with the requirements of CEN/TS 16976:2016 as detailed in Table 4.

Figure 2. Aerosol Diluter Model 3333-10.

The Aerosol Diluter provides a dilution ratio of 10 ±5%. An aerosol flow through the diluter of 1 L/min is driven by the attached CPC 3750-CEN (described below).The dilution flow is monitored by an internal mass flow meter, and controlled by an internal blower to keep the dilution ratio stable over the long term. The dilution ratio, diluter flow, and other parameters can be communicated to the CPC via an optional USB connection.

Section 3: Relative Humidity Measurement

Measuring the temperature and relative humidity (%RH) data in the sampled flow provides valuable data, from both a scientific perspective as well as with respect to complying with CEN requirements.

Performance Requirements

Table 5 provides performance requirements for a relative humidity sensor, used to measure the (%RH) of the air sample that enters the CPC inlet.

Table 5: Performance requirements for the relative humidity sensor.

Line item	Design aspects	Section: 16976	Section: 17434	CEN requirement	
1	Humidity monitoring at instrument inlet(s)	5.1.2	6.1.2	• The relative humidity of the sampled air must be monitored at the instrument inlets.	
2	Accuracy of relative humidity sensor	7.4		• The relative humidity sensor must be calibrated and able to confirm that measured humidity values between 20% and 80% are accurate to within…	3%
3			8.4		5%

The resolution of the discrepancy regarding the accuracy of the humidity measurement (lines 2–3) is subject to revisions by the CEN committees. TSI® flow meters fulfill the stricter accuracy of ±2%. The TSI®solution discussed below – the RHT3000 humidity and temperature sensor – fulfills the stricter accuracy of ±3%.

The TSI® Solution: Aerosol Humidity and Temperature Sensor Model RHT3000

Regardless of whether the ambient air is very humid or very dry, it is required to ensure that the air sample that enters the CPC inlet meets the requirement of <40% (3%) RH, as specified in CEN/TS 16976 Section 7.4 (see Table 3, line item 3).

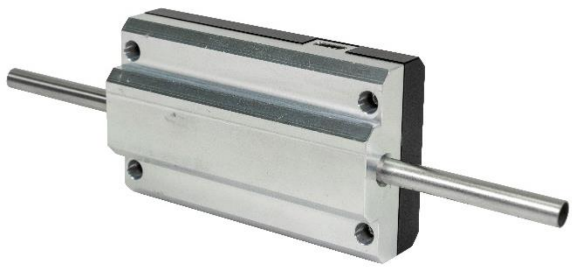

Figure 3. Aerosol Humidity and Temperature Sensor Model RHT3000.

The Aerosol Humidity and Temperature Sensor Model RHT3000 measures both relative humidity and temperature as the air passes into the CPC. It is designed to fit directly onto the inlet of TSI® CPCs, and also fits onto the TSI particle sizer relevant to CEN/TS 17434; see Section 5 for further details on that particle sizer. The sensor communicates with the instruments via a USB cable. When connected this way, %RH and temperature data are stored in the instrument right alongside particle data.

Section 4: Particle Number Concentration Measurement

Condensation particle counters (CPCs) are designed to measure the number concentration of airborne particles. CPCs can detect particles as small as a few nanometers in size (depending upon the design of the CPC), and have been used to monitor ambient air globally for years. A CPC is specifically required by CEN/TS 16976:2016 as the tool to use when measuring atmospheric aerosol.

CEN/TS 16976:2016 specifies requirements for CPCs that pertain to their design, performance, operation, and calibration. Maintenance actions to be performed by users are also specified by

CEN, but are outside the scope of this document. For guidance on regular maintenance, please refer to the relevant TSI® resources (especially manuals and maintenance guides), and/or contact TSI® Incorporated.

CPC: Design Requirements

Table 6: Design requirements of the CPC.

Line item	Design aspects	Section in 16976	CEN requirement
1	No photometric mode	5.2.2	CEN 16976 prohibits CPCs from using photometric mode when measuring the particle number concentration.
2	Counting mode	6.2	• All performance criteria refer to the CPC's performance when in counting mode (including coincidence correction).
3	No internal flow split		• The CPC must be a "full-flow" CPC, which is to say that the flow does not split internally within the CPC (i.e. in a way that does not readily permit an external flow rate check), and also that internal dilution is not used.
4	Working fluid		• The CPC must use n-butanol as its working fluid.
5	Data averaging		• Particle concentration data produced by the CPC must be averaged over an interval of one minute.
6	Clock synchronization		• The internal clock of the CPC must be able to be synchronized.
7	Required data and operating parameters		• The following parameters must be recorded by the CPC in 1 minute intervals: o Date and time of each concentration o Flow rate used in calculations o Raw concentration, before corrections are applied o Temperatures of two key stages in the CPC instrument o Temperature and pressure associated with the flow rate measurement o Flags of instrument warnings and errors

Performance Requirements

Within CEN/TS 16976:2016, Section 6.5 details not only *what* results the CPC must demonstrate when being tested on the various aspects of CPC performance, but also *how* the manufacturer should conduct those tests. In this Buyer's Guide this is split into four parts:

- Table 7 pertains to general CPC characteristics;
- Table 8 refers to the CPC inlet flow;
- Table 9 refers to CPC detection efficiency; and
- Table 10 pertains to CPC linearity.

All tables contain information both as to how a *manufacturer* must test CPC performance in these regards, and also the associated performance criteria for the CPC under test. Details pertaining to specific line items within these tables may be found in the text following the relevant table.

Table 7: Requirements for manufacturers when verifying general aspects of CPC performance.

Line item	Performance aspects	Section in 16976	CEN requirement
1	Test conditions: temperature	6.3	• Laboratory tests for CPC performance characteristics must be conducted such that the air surrounding the CPC is 20 – 23 °C. Exceptions are specified.
2	Number concentration measurement range	6.5.2	• The CPC must exhibit a concentration range (with or without coincidence correction) as defined by: ○ A lower concentration limit equal to or below 100 cm^{-3} ○ An upper concentration limit equal to or exceeding 10^4 cm^{-3} (including coincidence correction); ○ A dynamic range that covers at least three orders of magnitude in concentration.
3	Lower concentration detection limit	6.5.3	• The number concentration detection limit must be lower than 100 particles/cm^3.
4	Zero count rate	6.5.7	• The zero count rate (false count rate) of the CPC must be below one particle per minute, over the course of a 60 minute (or longer) test using an ULPA filter.
5	Response time	6.5.8	• A CPC's response time is a measure of how quickly it responds to a sudden change (i.e. step change) in particle number concentration. Section 6.5.8 defines this property, specifies how the must be conducted, and how the data must be analyzed. "$t_{rise} < 5$ s $t_{fall} < 5$ s $\left\|\frac{t_{rise}-t_{fall}}{t_{rise}}\right\| < 10\%\ or < 0.5\ s$"
6	Accuracy of temperature, pressure sensor calibration	6.5.10	• Temperature and pressure sensors must be appropriately calibrated to ensure that the measured values are accurate to within 3 K and 1 kPa, respectively.
7	Effect of failure of mains voltage	6.5.11	• In the case of loss of power the instrument parameters must be saved. • The instrument must automatically resume normal performance upon return of power.

Table 8: Requirements when verifying aspects of CPC performance related to the CPC's inlet flow.

Line item	Performance aspects	Section in 16976	CEN requirement
1	Test conditions: temperature	6.3	• Laboratory tests for CPC performance characteristics must be conducted such that the air surrounding the CPC is 20 – 23°C. Exceptions to this requirement are detailed in the standard where appropriate.
2	Inlet flow rate, test conditions: temperature	6.5.1	• The inlet flow rate of the CPC must be measured using a calibrated reference flow meter. • This measurement must be performed at an atmospheric pressure above 900 hPa, and at both 15°C and 30°C.
3	Inlet flow rate, test conditions: pressure		• The inlet flow rate of the CPC must be measured at a temperature in the range of 20 – 23°C. • This measurement must take place at two atmospheric pressures: one above 900 hPa and another that is at least 200 hPa lower than the first.
4	Inlet flow rate accuracy		• The inlet flow rate of the CPC must be measured using a reference flow meter that has an expanded uncertainty of ≤ 2 % (95 % confidence). • The inlet flow rate measured by that reference flow meter must differ from the nominal flow rate by ≤5%, and from the factory-certified flow rate by ≤2%.
5	Dependence of flow rate on supply voltage	6.5.9	• The inlet flow rate of the CPC must not vary by greater than 5% as the supply voltage to the CPC (or external pump, if used) varies. • This shall be determined by measuring the CPC inlet flow rate using supply voltages of 210 V, 230V, and 245V.

Table 9: Requirements when verifying CPC detection efficiency.

Line item	Performance aspects	Section in 16976	CEN requirement
1	Test conditions: temperature	6.3	• Laboratory tests for CPC performance characteristics must be conducted such that the air surrounding the CPC is 20 – 23°C. Exceptions to this requirement are detailed in the standard where appropriate.
2	Test conditions: pressure	6.5.5	• The detection efficiency of the CPC must be measured in accordance with ISO 27891, using silver particles of certain concentrations and sizes. • This measurement must be performed at two pressures (an atmospheric pressure above 900 hPa and a second pressure at least 200 hPa lower), and at two temperatures (15°C and 30°C).
3	Aerosol composition, concentration, and size		• The detection efficiency of the CPC must be measured in accordance with the requirements of ISO 27891. • The aerosol used must have specific characteristics as to its size, concentration, and chemical composition. • The CPC must exhibit a D_{50} of 7 nm ±0,7 nm. • The CPC must exhibit a D_{90} of <14 nm.
4	Upper particle size detection limit	6.5.6	• The detection efficiency of the CPC for large particles (1000 nm) must be determined. • The CPC must exhibit >90% detection efficiency at 1000 nm ±100 nm.

Measuring the number concentration of aerosols depends on the ability to detect that a particle is present. As suggested by their name (Condensation Particle Counters), CPCs condense a vapor onto particles to grow them large enough to be detected. Different CPC designs can do this successfully for particles of different size ranges. The D50 of a CPC is the particle size at which the CPC can successfully detect 50% of the particles. The D50 is a fundamental specification of a CPC, and varies by CPC model.

As mentioned earlier in this document ("Anticipated Changes to the CEN Standards" portion of the Introduction), one of the anticipated changes to CEN/TS 16976 is that the D50 of the CPC will change from 7 nm (as shown in Line 3) to 10 nm. Refer to the section "The TSI® Solution: Condensation Particle Counter (CPC) Model 3750-CEN7," below, for further details.

Table 10: Requirements when verifying linearity of CPC measurements.

Line item	Performance aspects	Section in 16976	CEN requirement
1	Test conditions: temperature	6.3	• Laboratory tests for CPC performance characteristics must be conducted such that the air surrounding the CPC is 20 – 23°C. Exceptions to this requirement are detailed in the standard where appropriate.
2	Test conditions (pressure)	6.5.4	• The linearity of the CPC response must be determined by comparing CPC performance to that of a reference instrument. The aerosol used in this test must be silver, and have specified number concentrations. • This measurement must be performed at two pressures (an atmospheric pressure above 900 hPa and a second pressure at least 200 hPa lower), and at two temperatures (15°C and 30°C).
3	Aerosol composition and size		• When assessing CPC linearity, the procedure in ISO 27891 must be followed. • The aerosol used for assessing CPC linearity must be composed of silver, and be 40 nm ±10 nm in size.
4	Number concentration of calibration aerosol		• CPC linearity should be assessed by presenting the CPC with "challenge" concentrations of approximately 1,000 particles/cm^3, and stepping up by a factor of two until the final measurement is taken at nearly the upper concentration limit of the CPC when in count mode.
5	Coincidence correction		• Number concentration measurements made during the assessment of CPC linearity must be coincidence corrected.
6	Multiply-charged particles		• Corrections for multiply-charged particles should be made if they are found to be present and if an aerosol electrometer is used as a reference instrument.
7	Data analysis		• The data from the CPC linearity assessment must be analyzed by performing a regression analysis. • The resulting slope must be 1 ±0,05. • The resulting residuals must be <4%.

Regular Calibration Requirements

All CPCs used in CEN-compliant measurement efforts are required by CEN/TS 16976:2016 Section 9.2.3 to undergo annual calibration.

Table 11: Requirements of annual CPC calibration.

Line item	Calibration aspects	Section in 16976	CEN requirement
1	Plateau region	9.2.3	• The detection efficiency of the CPC in the plateau region of its detection efficiency curve must be assessed on both an "as-found" basis and also after any maintenance is performed. • This assessment shall be in accordance with the requirement sof ISO 27891, and shall use silver particles with a size of 30 – 50 nm. • The resulting CPC detection efficiency must be $0{,}95 \leq \eta(D_p) \leq 1{,}05$. • If the CPC exhibits a detection efficiency outside of that range, further maintenance is required.
2	Linearity		• CPC linearity must be assessed using the same procedure as was used for assessing plateau region counting efficiency. • The residuals resulting from a regression analysis of this data must be <4%. • If the residuals exceed 4%, further maintenance is required.

In general, CPCs require at least annual cleaning and calibration services, which is usually offered by the manufacturer. In addition calibration centers, such as members of the European Center for Aerosol Calibration and Characterization (ECAC), may be available to conduct CEN/TS specific services.

The TSI® Solution: Condensation Particle Counter Model 3750-CEN7

The Condensation Particle Counter (CPC) Model 3750-CEN7 complies with the requirements specified in CEN/TS 16976:2016.

CPC Model 3750-CEN7 builds on the legacy of multiple generations of butanol-based CPCs from TSI®. It is designed for 24/7/365 operation, can store data internally or send to network computers, and responds quickly to rapid changes in aerosol concentrations.

Due to their expertise at calibrating CPCs according to the requirements of CEN/TS 16976, TSI® chose the World Calibration Center for Aerosol Physics (WCCAP) located at the Leibniz Institute for Tropospheric Research (TROPOS) to conduct CEN/TS-specific calibrations. Every new compliant CPC is routed through this member of the European Center for Aerosol Calibration and Characterization (ECAC). Subsequent calibrations are available on demand or as service contracts from TSI.

In between annual calibrations, users can conduct preventative maintenance on a pre-emptive and/or as-needed basis. Guidance in this regard is available in the Preventative Maintenance Guide for the CPC 3750. This guide may be requested here.

Figure 4. Condensation Particle Counter Model 3750-CEN7.

The flow through the CPC is controlled by a critical orifice (see Table 9 line items #2–4, Table 10 line item #2, and Table 11 line item #2). As long as the vacuum applied to the vacuum port of the CPC is sufficiently low, flow rate dependence on inlet pressure is small (<5% down to 70 kPa inlet pressure) and predictable. For more details, refer to the TSI Application Note titled “Flow Rate Correction for the Model 3790 Engine Exhaust Condensation Particle Counter (EECPC).” The principles described there apply to all CPCs that have inlet flows controlled by a critical orifice. Because the CPC flow is controlled by a critical orifice as described above, it is not dependent upon the supply voltage (Table 9 line item #5).

Anticipated Change to CEN/TS 16976

The detection efficiency in the 2016 revision of CEN/TS 16976 requires a D50 around 7 nm. Back in 2016 the commonly used TSI CPC model 3772 was recalibrated from 10 nm to 7 nm for this purpose. The successor CPC model 3750, released in 2017, was then designed with a D50 of 7 nm. A future revision of CEN/TS 16976 is planned to change this setting to 10 nm. Moving forward, TSI offers model numbers 3750-CEN7 and 3750-CEN10 for purchase to serve today’s and future needs.

Section 5: Particle Size Distribution Measurement

A Mobility Particle Size Spectrometer (MPSS) measures the size distribution of aerosol particles. It does this by performing several different functions in concert with each other. While all of these functions are performed simultaneously by the MPSS system, they are described here in the order in which an individual particle passes through them:

Inlet impaction	At the instrument inlet an impactor removes the largest particles from the sample stream. This prevents the larger particles – which can be highly charged – from degrading the accuracy of the "mobility classification" step described below.
Aerosol neutralization	Provides the incoming aerosol with a known (electrical) charge distribution. Known percentages of particles will have no charge, +1 charge, -1 charge, and so on. The distribution of charges varies by particle size, as larger particles are better able to carry multiple charges.
Mobility classification	This step size-selects the particles by taking advantage of their behavior in an electrical field, and the known charge state imparted in the "neutralization" step. This step moves through particle sizes over time by sweeping through a range of voltages in one specific component the Differential Mobility Analyzer (DMA). At any given moment, only particles of one specific size are selected to exit the DMA.
Particle counting	Once the particles have been size-selected and exit the DMA, they are counted using a CPC. When the DMA emits size-selected particles, the CPC counts those particles. When these two functions work together, a size distribution can be built. CEN/TS 17434:2020 specifies that the CPC used in an MPSS system must be compliant with CEN/TS 16976:2016; please see Table 12 line item #1.

Due to the need to perform all of the above functions (as well as perform the necessary data processing), MPSS systems are complex instruments. CEN/TS 17434:2020 specifies requirements for MPSS systems that pertain to their design, performance, and annual calibration. Maintenance actions to be performed by users are also specified by CEN, but are outside the scope of this document. For guidance on regular maintenance, please refer to the relevant TSI® resources (especially manuals and maintenance guides), and/or contact TSI® Incorporated.

Design requirements

Sections 6.2.6 and 7.1 specify the performance requirements for MPSS systems. In this Buyer's Guide this is split into two parts:

- Table 12 pertains to requirements of two MPSS components (the CPC and the DMA), and
- Table 13 pertains to the remaining elements of an MPSS system.

Details pertaining to specific line items within these tables may be found in the text following the relevant table.

Table 12: Design requirements of the CPC and DMA components of an MPSS.

Line item	Design aspects		Section in 17434	CEN requirement
1	CPC	Compliance w/ CEN/TS 16976	7.1	• The CPC used in an MPSS must be compliant with all the requirements of CEN/TS 16976.
2	CPC	CPC characterization	6.2.6	• The detection efficiency curve of the CPC used in an MPSS must be determined in accordance with CEN/TS 16976.
3	DMA	General design	7.1	• The DMA in an MPSS must be cylindrical. • The sheath and excess air must flow in a closed loop that includes a HEPA filter and dryer.
4	DMA	Temperature and humidity measurements	7.1	• Both aerosol and sheath flows within an MPSS must include temperature and relative humidity measurements.
5	DMA	Humidity requirements	7.1	• The sheath air must have a relative humidity <40% at the outlet of the DMA.
6	DMA	Pressure measurement	7.1	• The absolute pressure must be measured either at the aerosol inlet or in the sheath air flow.
7	DMA	Size resolution	7.1	• The idealized (theoretical) size resolution of the DMA should be: $\frac{\Delta Z_P}{Z_p^*} \leq 0.125 \; or \; \frac{Q_S}{Q_A} \geq 4$

Table 13: Design requirements of the remaining elements of an MPSS system (i.e. aside from CPC and DMA).

Line item	Design aspects	Section in 17434	CEN requirement
1	Pre-separator	7.1	• A pre-separator should be used if the aerosol to be measured includes a nontrivial amount of particles larger than can be measured by the particle sizer. • The pre-separator can be an impactor or cyclone, and may be included either in the particle sizing instrument or in the sampling system.
2	Neutralizer		• A radioactive ionizer is recommended; a bipolar charge distribution may be assumed. • Other ionizers should have charge distributions adapted to mach that of a radioactive ionizer.
3	High voltage supply		• It is recommended that the voltage output of the high voltage supply be able to be measured independently.
4	Delay time check		• An MPSS system must have the capability to perform, at least for purposes of calibration, an upscan and downscan at high size resolution.
5	Data deconvolution		• An MPSS system must have at least 16 size bins per size decade (order of magnitude in particle size. • The size bins must be geometrically equally spaced.
6	Time to measure a particle number size distribution		• An MPSS system must be able to perform a measurement of the particle size distribution in two to ten minutes.
7	Data availability		• An MPSS system must be capable of providing its data at ACTRIS levels 0, 1, and 2.

8	Diffusion correction in MPSS software for sampling system losses	6.2.5	• Diffusion losses must be adequately corrected for to ensure data accuracy and harmonization.
			• A common method utilizing the concept of equivalent length is recommended.
			• This can be accomplished in one of two ways:
			  ○ Applying a correction for the entire system after having disabled any diffusion correction performed in the commercial software; or,
			  ○ Inserting site-specific parameters into the commercial software, if the software permits this.

Performance Requirements

Within CEN/TS 17434:2020, Section 7.2 specifies not only what results the MPSS must demonstrate when being tested on the various aspects of MPSS performance, but also *how* the manufacturer should conduct those tests. In this Buyer's Guide this is split into two parts:

- Table 14 pertains to aerosol flow and number concentraton measurements;
- Table 15 pertains to the size range, and the accuracy of both particle size and particle size distribution measurements.

All tables contain information both as to how a manufacturer must test MPSS performance in these regards, and also the associated performance criteria for the MPSS under test. Details pertaining to specific line items within these tables may be found in the text following the relevant table.

Table 14: Performance requirements pertaining to aerosol flow within, and particle number concentration measured by, the MPSS.

Line item	Performance aspect	Section in 17434	CEN requirement
1	Actual vs. calibration aerosol flow rate	7.2.1	• The aerosol flow rate of an MPSS system must be measured with a reference flow meter. • The reference flow meter must have a relative uncertainty of ≤2% at the relevant flow rate. • The aerosol flow rate measurement must differ from the nominal aerosol flow rate by ≤5%.
2	DMA flow conditions	7.2.6	• Sample flow inside the DMA must be laminar. • If flow is laminar and an electric field is not applied, particles entering the DMA cannot reach the DMA outlet. • Because of this, a zero-check test can confirm laminarity within the DMA. • The DMA can be concluded to have laminar flow if the CPC measures <0,01 cm^{-3} for 10 seconds or longer.
3	False background number concentration	7.2.5	• The false background measurement of an MPSS system must be assessed. • The false background is the number concentration measured over all size bins scanned by the MPSS. • This number concentration must be <0,01 cm^{-3} over the course of a 10-minute measurement of air that has passed through a HEPA filter.

4	Accuracy of integrated particle number concentration	7.2.4	• The number concentration measured by the MPSS must be compared to a reference CPC; this reference must be compliant with CEN/TS 16976.
			• The comparison must be done using ambient air.
			• The data must be analyzed via linear regression.
			• The result from this analysis must demonstrate that the MPSS-CPC comparison has:
			  o A slope between 0,9 and 1,1 (forced through origin)
			  o An R^2 value ≥0,9

The laminarity of DMA sheath flow is critical as described in line item #2. Experience has shown that using ambient air when high concentrations of particles ~10 nm (or smaller) are present can produce biased test results for many DMAs. Best practice is to utilize controlled and/or well-characterized aerosol sources, with stable size distributions that do not contain high concentrations of sub-10 nm particles.

Table 15: Performance requirements pertaining to the particle size range, and to the accuracy of both particle size measurements and particle size distribution measurements made by the MPSS.

Line item	Performance aspects	Section in 17434	CEN requirement
1	Particle size range	7.2.2	• The particle size range that a particular MPSS is capable of scanning over can be determined theoretically, based upon geometric parameters and high voltage range. • An MPSS system must be able to cover the range from 10 nm to 800 nm in electrical mobility diameter.
2	Particle size calibration accuracy	7.2.3	• The particle sizing accuracy of an MPSS system must be investigated experimentally. • Certified monodisperse polystyrene latex sphere (PSL) particles must be used for this investigation; it is recommended to use PSL particles between 100 and 300 nm in size. • The size of these PSL particles, as measured by the MPSS, must differ from the manufacturer-certified size of the PSL by ≤3%. • If the measured size differs from the certified size of the latex particles, the MPSS sheath air flow rate may be adjusted to bring the agreement to within 3%.
3	Particle number size distribution accuracy	7.2.7	• The accuracy of particle size distribution measurements made by an MPSS system must be investigated experimentally. • This is done by comparing the MPSS' measurements to that of a calibrated reference MPSS system when both are sampling atmospheric aerosol. • When comparing the resulting data, particle concentrations measured by the two systems are compared one size bin at a time. Acceptance criteria depend upon particle size: o ≤50% for size bins in the range 10 nm to 20 nm o ≤10% for size bins in the range 20 nm to 200 nm o ≤20% for size bins in the range 200 nm to 800 nm

Annual Calibration Requirements

All Mobility Particle Size Spectrometer (MPSS) systems used in CEN-compliant measurement efforts are required by CEN/TS 17434:2020 to undergo annual calibration. In this Buyer's Guide this is split into two parts:

- Table 16 pertains to general characteristics of an MPSS system;
- Table 17 pertains to flows within an MPSS system, and to the comparison of an MPSS system's measurements with those of reference instruments.

Details pertaining to specific line items within these tables may be found in the text following the relevant table.

Table 16: Requirements of annual MPSS calibration that pertain to general characteristics of an MPSS system.

Line item	Calibration aspects	Section in 17434	CEN requirement
1	False background concentration check (MPSS)	7.2.5	• During MPSS calibration, the false background concentration of the MPSS system must be measured. • This measurement is performed by connecting a HEPA filter to the MPSS inlet and allowing the MPSS to measure the particle size distribution over the course of ten minutes. • The resulting number concentration must be <0,01 cm^{-3}
2	Mean false background concentration check (CPC)	10.3.7	• A false background concentration check of the CPC should be done only if the false background concentration of the MPSS (above) fails. • To pass, the CPC must measure an average count rate of fewer than 15 counts per minute.
3	Sensors calibration	10.3.4	• During MPSS calibration, the sensors that measure the relative humidity both in the sheath loop and the aerosol flow must be calibrated to ensure that the measurements are accurate to within ±3%.
4	CPC calibration	10.3.5	• The CPC used within the MPSS must be calibrated in accordance with the requirements of CEN/TS 16976.
5	Delay time check	10.3.6	• To ensure that the delay time between DMA and CPC is correct, an upscan and downscan must be performed. • If the particle size distribution measurements made during the upscan and downscan are identical, the delay time is accurate.
6	Particle size calibration accuracy	7.2.3	• During MPSS calibration, the particle sizing accuracy of the MPSS system must be investigated experimentally. • This investigation must utilize polystyrene latex sphere (PSL) particles; refer to ISO 15900. • The size of these PSL particles, as measured by the MPSS, must differ from the manufacturer-certified size of the PSL by ≤3%. • If the measured size differs from the certified size of the latex particles, the MPSS sheath air flow rate may be adjusted to bring the agreement to within 3%.

Table 17: Requirements of annual MPSS calibration that pertain to flows within an MPSS system, and to the comparison of that system's final measurements to those of reference instruments. .

Line item	Calibration aspects	Section in 17434	CEN requirement
1	Aerosol flow rate calibration (MPSS)	10.3.2	• The aerosol flow rate of an MPSS system must be measured during MPSS calibration. • The measured flow rate must not differ from the nominal flow rate by 5% or greater.
2	Aerosol flow rate calibration (CPC)	10.3.3	• The inlet flow rate of the CPC that is used in an MPSS system must be measured during MPSS calibration. • The CPC inlet flow and the MPSS inlet flow must be identical to each other, within the range of uncertainty.
3	Flow condition check	7.2.6	• Sample flow inside the DMA must be laminar. • If flow is laminar and an electric field is not applied, particles entering the DMA cannot reach the DMA outlet; a zero-check test can confirm laminarity within the DMA. • The DMA can be concluded to have laminar flow if the CPC measures <0,01 cm^{-3} for 10 seconds or longer.
4	Leak check	10.3.8	• The potential for leaks in the MPSS must be assessed. • The system may be concluded to be free of leaks if: o The MPSS aerosol (inlet) flow rate and the CPC inlet flow rate are equal, ***and*** o The mean false background check was passed.
5	Comparison to a reference instrument	7.2.4	• The number concentration measured by the MPSS must be compared to a reference CPC; this reference must be compliant with CEN/TS 16976. • The comparison must be done using ambient air. • The data must be analyzed via linear regression. • The result from this analysis must demonstrate that the MPSS-CPC comparison has: • A slope between 0,9 and 1,1 (forced through origin) o An R^2 value ≥0,9
6	Comparison to a reference MPSS	7.2.7	• The accuracy of particle size distribution measurements made by an MPSS system must be investigated experimentally. • This is done by comparing the MPSS' measurements to that of a calibrated reference MPSS system when both are sampling atmospheric aerosol. • When analyzing the resulting data, particle concentrations measured by the two systems are compared one size bin at a time. Acceptance criteria vary by particle size: o ≤50% for size bins in the range 10 nm to 20 nm o ≤10% for size bins in the range 20 nm to 200 nm o ≤20% for size bins in the range 200 nm to 800 nm

In general, annual cleaning and calibration service is recommended for MPSS systems, and is in fact required by CEN/TS 17434:2020 as detailed above. Such service is usually offered by the manufacturer. In addition calibration centers, such as the World Calibration Center for Aerosol Physics (WCCAP) at Leibniz Institute for Tropospheric Research (TROPOS), may be available to conduct CEN/TS specific services.

The TSI® Solution: Scanning Mobility Particle Sizer™ Spectrometer for Ambient Air Monitoring, Model 3938W50-CEN7

While "Mobility Particle Size Spectrometer" (MPSS) is the general term that CEN/TS 17434 uses to describe such instruments, the TSI® instrument with the same capabilities is called a Scanning Mobility Particle Sizer™ (SMPS™) spectrometer.

The SMPS™ Model 3938W50-CEN7 complies with the requirements specified in CEN/TS 17434:2020.

SMPS™ Model 3938W50-CEN7 builds on the legacy of multiple generations of mobility particle sizers from TSI®. It is capable of scanning from 10 – 800 nm in a single scan, automatically resumes operation following power outage, and provides measurement data in a comprehensive export format, which can be easily integrated into the databases of the monitoring station.

Due to their expertise at calibrating MPSS systems according to the requirements of CEN/TS 17434, TSI chose the World Calibration Center for Aerosol Physics (WCCAP) located at the Leibniz Institute for Tropospheric Research (TROPOS) to conduct CEN/TS-specific calibrations. Every new compliant SMPS™ system is routed through this member of the European Center for Aerosol Calibration and Characterization (ECAC). Subsequent calibrations are available on demand or as service contracts from TSI.

Figure 5. Scanning Mobility Particle Sizer™ Spectrometer Model 3938W50-CEN7

Anticipated Change to CEN/TS 16976

As described at the end of Section 4, a future revision of CEN/TS 16976 is planned to change the counting efficiency of the CPC from 7 nm setting to 10 nm. Because CEN/TS 17434:2020 requires that an MPSS system include a CPC that is compliant with CEN/TS 16976, the change in the D50 requirement for CPCs will also affect MPSS systems. Moving forward, TSI offers model numbers 3938W50-CEN7 and 3938W50-CEN10 for purchase. These will each include a CPC with the corresponding cutpoint – as a component in SMPS™ systems – to serve today's and future needs.

The Full TSI® Solution for Compliance with CEN/TS 16976:2016 and 17434:2020

Making ultrafine particle measurements in compliance with the CEN standards requires the right tools. TSI® offers a full solution that includes sampling, drying, and diluting the aerosol, as well as measurement of relative humidity and temperature, particle number concentration, and particle size distribution.

Each of these components was developed with CEN compliance in mind, and is based on TSI's decades of experience designing, manufacturing, and supporting particle measurement instrumentation. Compliance of the full TSI® solution with the requirements of CEN/TS 16976:2016 and 17434:2020 is summarized in Table 18.

Figure 6. The Ultrafine Particle Monitoring solution from TSI. This solution is compliant with CEN standards 16976 and 17434, as summarized in Table 18. Diluter (optional) and pump not shown.

Table 18: Summary of compliance status for all components of TSI's full solution for CEN-compliant monitoring of atmospheric ultrafine particles.

System component		Tables	Compliance with all relevant CEN requirements
Name	**Model**		
Sampling system for atmospheric aerosol	3750200	1–3	✓
Aerosol diluter	3333-10	4	✓
Relative humidity and temperature sensor	RHT3000	5	✓
Condensation Particle Counter (CPC)	3750-CEN7	6–11	✓
Scanning Mobility Particle Sizer (SMPS™) system*	3938W50-CEN7	12–17	✓

*Referred to as MPSS within the CEN standards

Both the CPC and the SMPS™ system undergo CEN/TS-specific calibrations at the World Calibration Center for Aerosol Physics (WCCAP), located at the Leibniz Institute for Tropospheric Research (TROPOS). WCCAP is a member of the European Center for Aerosol Calibration and Characterization (ECAC), and is an ACTRIS calibration facility. From design through calibration, the TSI ultrafine particle monitoring solution delivers full CEN compliance.

Additional Accessories

A pump is required to drive the system flows, and an optional catalytic vapor filter removes butanol vapor from the exhaust of the CPC and SMPS™ system. These accessories do not have requirements set for them by the CEN/TS standards. Please refer to the Solutions Brochure (US) and (A4) for more information on these accessories.

For further information on any component, please refer to the Solutions Brochure (US) and (A4), as well as specification sheets for all system components. Please feel free to contact TSI® at any time with questions, or for assistance in configuring an ultrafine particle monitoring solution for your specific needs.

References

1. CEN/TS 16976:2016. Ambient air – Determination of the particle number concentration of atmospheric aerosol.
2. CEN/TS 17434:2020. Ambient air – Determination of the particle size spectra of atmospheric aerosol using a Mobility Particle Size Spectrometer (MPSS).
3. UFP Solutions brochure US and A4.
4. Sampling System for Atmospheric Aerosol 3750200 specification sheet, US and A4.
5. Aerosol Diluter 3333-10 specification sheet,. US and A4
6. Aerosol Humidity and Temperature Sensor RHT3000 specification sheet, US and A4.
7. CPC 3750-CEN specification sheet, US and A4.
8. SMPS 3938W50-CEN specification sheet, US and A4.
9. “Flow Rate Correction of the Model 3790 Engine Exhaust Condensation Particle Counter (EECPC),” Application Note EECPC-001, US and A4.

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