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TECHNICAL NOTE

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Performance evaluation of the national air quality testing services V2000 Condensation Particle Counter

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ABSTRACT

The Condensation Particle Counter (CPC) is an effective instrument for measuring the number concentration of aerosol particles in different environments. With only a few exceptions, CPCs are bench instruments with limited portability for use in the field, and have a cost that prevents their use in large numbers for distributed air quality measurements. This has motivated the development of compact and cost-effective CPCs that are already available in the market. Here we test the performance of such a CPC, designed and built by National Air Quality Testing Services Ltd (NAQTS), Lancaster, UK, which is a part of the V2000 compact air quality monitor that also includes gas sensors. The tests were carried out using monodisperse particles produced by atomization and electrical mobility classification. We found that the NAQTS V2000 CPC has a 50% detection efficiency for particles having diameter of ca. 14 nm. Our results also show that the coincidence error of the core CPC occurs at concentrations higher than 1×10^4 #/cm^{-3}. Considering that the standalone CPC employs an ejector pump that provides a nominal dilution factor between 20 and 50 at its inlet, the coincidence error threshold of the system when sampling particles from ambient air is 2–5 × 10^5 #/cm^{-3}. To extend its range for aerosols with particle concentrations by one order of magnitude higher, and thus expand its capabilities for a wide range of applications, we provide a simple correction equation. Overall, our results demonstrate that the NAQTS V2000 CPC is a highly effective instrument, and considering that it is currently the most cost-effective CPC in the market, to the best of our knowledge, makes it a highly attractive solution for air quality monitoring.

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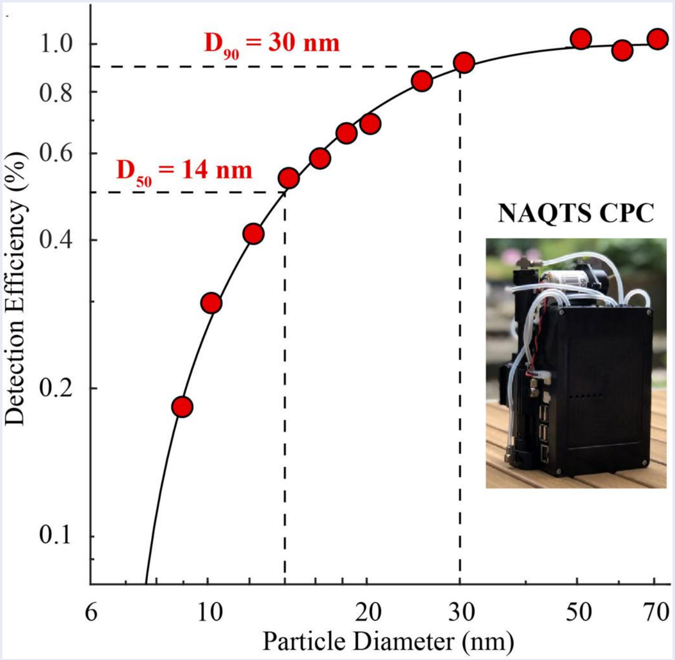

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1. Introduction

Airborne particles are a major source of concern as they can affect climate, in a direct or indirect manner, and human health (Kim, Jahan, and Kabir 2013; Neuberger et al. 2004; Rai 2016; Thurston et al. 2017). The chemical composition of ambient aerosol particles can vary depending on their sources and the processes they undergo in the atmospheric environment, while their size can range from few nanometers to several tens of micrometers (Finlayson-Pitts et al. 2020; Harrison 2020). Within this size range, ultrafine particles (UFPs; i.e., particles smaller than 100 nm) can severely affect human health as they penetrate deep into the respiratory system (Calderón-Garcidueñas et al. 2008; Ohlwein et al. 2019; Rosenlund et al. 2009).

There are several methods for measuring the concentration of aerosol particles. Optical methods, relying on the ability of the particles to scatter light, are often used for online measurements of their number concentration. These methods, however, are not effective for UFPs, as their scattering efficiency is extremely low due to their small size, warranting the use of other techniques for detecting and counting them in ambient air (McMurry 2000). One of the first instruments for measuring the number concentration of aerosol particles having diameters down to a few nanometers is the Aerosol Electrometer (AE; Whitby and Clark 1966), which requires the sampled particles be unipolarly charged with a known number of elementary charges. This limitation, together with the demand for measuring particles regardless of their charging state, motivated the development of the Condensation Particle Counter (CPC; Agarwal and Sem 1980). The CPC employs a saturation-condensation system where the sampled particles, having sizes down to a few nanometers, are grown by condensation of a working fluid, such as an alcohol or water, to droplets that can be optically detected. Despite the great potential of CPCs, their high cost and low portability currently limit their widespread use.

To overcome this constraint, a number of instrument manufacturers have introduced portable and more compact CPCs. In the early 2000s, Thermo-Systems Engineering Inc. (TSI), based in Shoreview, USA, marketed the 3007 CPC (Hameri et al. 2002), whereas more recently Brechtel Manufacturing Inc. (BMI), in Hayward, USA, has introduced the MCPC 1720 CPC (BMI. 2016), and NAQTS Ltd, Lancaster, UK developed a portable CPC that is part of the V2000 air quality monitor (NAQTS. 2019). The latter is a cost-effective system that combines a CPC with a number of sensors that can measure the concentrations of different air quality-related gases (i.e., CO, CO_2, NO_2, ozone and volatile organic compounds). In addition, the system is equipped with noise, relative humidity, and temperature sensors, as well as a 3D accelerometer and 3D gyro for vibration measurements so that it can be employed on mobile platforms. The compact size, together with the ability to measure a range of pollutants makes the V2000 air quality monitor suitable for use in indoor and outdoor environments, but also for vehicle emissions analysis under real-life conditions. In view of the latter application, it is important for the V2000 CPCs to adhere to the particle number (PN) measurement protocol for automotive engine testing, described by the Particle Measurement Programme (PMP; Terres et al. 2018). Currently this requires use of CPCs with a 50% and a 90% counting efficiency for particles having diameters (D_{50} and D_{90}, respectively) of 23 and 41 nm, with future regulations demanding D_{90} to be pushed down to 15 nm (Giechaskiel et al. 2021).

Each of the compact CPCs mentioned above has specific capabilities and features that make them suitable for certain applications. The NAQTS V2000 CPC can measure high concentrations of particles, fulfilling demands for vehicle emissions studies. The TSI 3007 CPC is optimized for portability and use for outdoor measurements, whereas the BMI MCPC 1720 CPC is very compact and has a fast response, facilitating use onboard lightweight and fast-moving mobile platforms (e.g., Unmanned Aerial Systems). We should note here that the NAQTS V2000 and the BMI MCPC 1720 CPCs actively control the temperatures both in the saturator and the condenser. This is in contrast to the approach followed in the TSI 3007 CPC, which provides a constant electrical power to the thermoelectric elements used to achieve a temperature difference between its saturator and condenser. Despite the simplicity of this system, however, the temperature difference between the saturator and the condenser of the TSI 3007 CPC can be affected when the ambient temperature changes, thus affecting its counting accuracy for particles smaller than ca. 20 nm, and consequently altering its D_{50} (Bezantakos and Biskos 2022). What also distinguishes the NAQTS V2000 CPC is that its market price is a fraction, ranging from 1/2 to 1/5, of that of the TSI 3007 and the BMI MCPC 1720 systems.

The NAQTS air quality monitor, including its CPC, has recently been employed in a number of indoor and outdoor air quality studies (Lim et al. 2022; Molden et al. 2023), but in contrast to the other portable CPCs its performance has not been investigated yet. To fill this gap, here we report measurements of its counting efficiency and coincidence error, and compare its performance with published data for the TSI 3007 and the BMI MCPC 1720 systems. The rest of the article is organized as follows: Section 2 describes the methods followed for the characterization of the CPC, Section 3 discusses the main results of our work, and Section 4 provides a summary of the most important conclusions.

2. Methods

2.1. Experimental setup

The experimental setup used to characterize the NAQTS V2000 CPC is shown in Figure 1. In brief, polydisperse ammonium sulfate particles were produced by an atomizer (TSI Model 3076; TSI, Shoreview, USA) using an ammonium sulfate solution (0.1%w/v) and air, coming from a compressor, as a carrier gas. The resulting aerosol was dried by passing it through a silica gel diffusion dryer, and charge-neutralized through a ^{85}Kr source aerosol neutralizer (TSI Model 3077 A; TSI, Shoreview, USA). Subsequently, the particles were size-selected by a Differential Mobility Analyzer (DMA; TSI Model 3085; TSI, Shoreview, USA), operated at a constant sheath flow of 12.00 lpm. The aerosol flow through the DMA was varied from a few hundreds cm^3/min to a maximum of 1.20 lpm, controlled by an open dilution system located downstream the DMA (cf. Figure 1). Doing so resulted in sheath-to-aerosol flow ratios of 10:1 and higher in the DMA, ensuring narrow size distributions of the resulting monodisperse particles under all experimental conditions.

The monodisperse aerosol flow downstream the DMA was directed to a reference aerosol electrometer (Ioner Model EL-5030; RAMEM S.A, Torrejón de Ardoz, Spain) and the NAQTS V2000 CPC, so that the detection efficiency of the latter was determined when selecting particles of different sizes by the DMA. The sample flow rates of the reference electrometer and the CPC were fixed at 1.30 and 1.25 lpm. The open dilution system introduced downstream the DMA was used to control the particle number concentrations to desired levels.

The experimental procedure we followed included the following steps. First, the test CPC was warmed-up for about 30 min, while the atomizer was inactive. When, it started reporting almost zero counts, the electrometer was zeroed and a constant voltage was set to the DMA in order to select monodisperse particles having sizes from 9 to 70 nm. After that, production of the polydisperse particles from the atomizer was started by opening the valve of the compressed air. The concentration of the monodisperse particles was maintained in the range of 4×10^3 to 8×10^3 #/cm^3 for all the measurements we carried out to determine the detection efficiency of the CPC. Measurements of both the CPC and the reference electrometer were recorded at a frequency of 1 Hz. Data were collected for at least 8 min when the atomizer was switched on (i.e., actual measurements). Before the start of the measurements (i.e., before turning on the atomizer) and at the end of each experiment (i.e., when the atomizer was switched off), data were recorded for at least 60 s. This procedure ensured adequate monitoring of any potential electrometer drifts, thus reducing the uncertainty of the measurement. The detection efficiency of the NAQTS V2000 CPC was determined as the fraction of the number concentration detected by the CPC and that determined by the electrometer when both instruments sampled monodisperse particles. In addition, we investigated the effect of particle coincidence (i.e.,

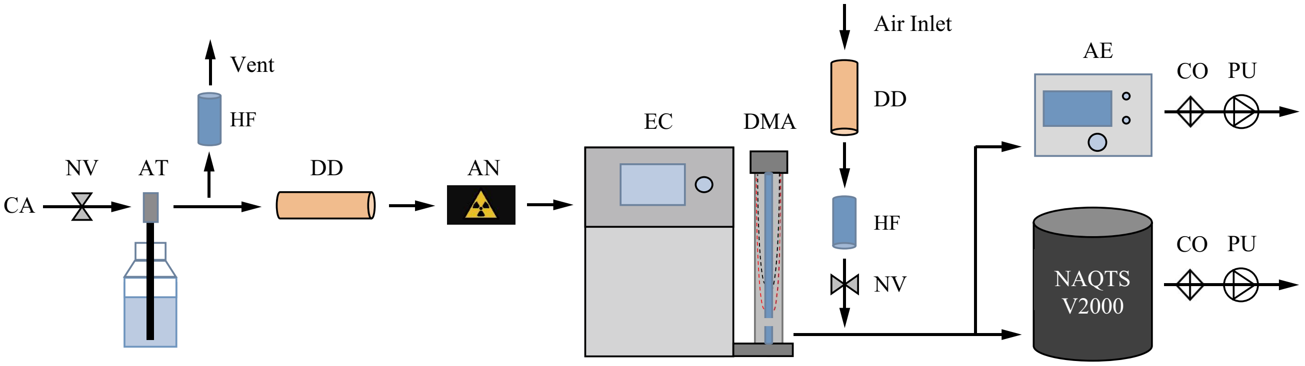

Figure 1. Flow diagram of the experimental setup used to determine the detection efficiency of the NAQTS V2000 CPC. Key: CA: Compressed Air; NV: Needle Valve; AT: Atomizer; HF: HEPA Filter; DD: Diffusion Dryer; AN: Aerosol Neutralizer; DMA: Differential Mobility Analyzer; EC: Electrostatic Classifier; AE: Aerosol Electrometer; CO: Critical Orifice; PU: Pump.

when more than one particles pass simultaneously through the detection volume of the CPC optical detector; referred to as coincidence error) on the measurements by feeding the CPC with 60-nm monodisperse particles (for which the detection efficiency is 100% when the concentration is low enough) over a wide range of concentrations.

2.2. Instrumentation

The NAQTS V2000 CPC is equipped with a special inlet for diluting the sample flow with an ejector diluter (cf. Figure 2a). Using compressed and filtered air provided by a pump through the ejector nozzle at a high speed creates a partial vacuum at the instrument inlet that draws the aerosol sample and simultaneously dilutes it. Part of the diluted flow (a few tens of cm^3/min) is then sampled coaxially by a thin nozzle located downstream the ejector (i.e., sampling inlet), while the excess flow (i.e., created at the instrument inlet by the ejector diluter) escapes though open ports, surrounding the thin sampling nozzle.

The rest of the instrument is a mixing-type CPC (Kousaka et al. 1982; Mavliev 2002; Wang et al. 2002), where the sample flow downstream of the thin sampling inlet is mixed with a saturated flow of isopropyl alcohol coming from the saturator of the instrument. The saturated flow, laden with the sampled aerosol particles, is directed through the condenser and the optical detector of the instrument. A second pump regulates the sample flow (20–50 cm^3/min), the saturator flow (set as a ratio of 75/25% to the sample flow) and other secondary flows within the instrument (e.g., optics purge flow of 10–20 cm^3/min) by a combination of orifices and pressure transducers. One of the transducers measures the pressure drop along the sampling inlet of the instrument in order to determine the aerosol-laden sample flow, which is used to determine the particle number concentration from the raw CPC counts. In addition, absolute pressure

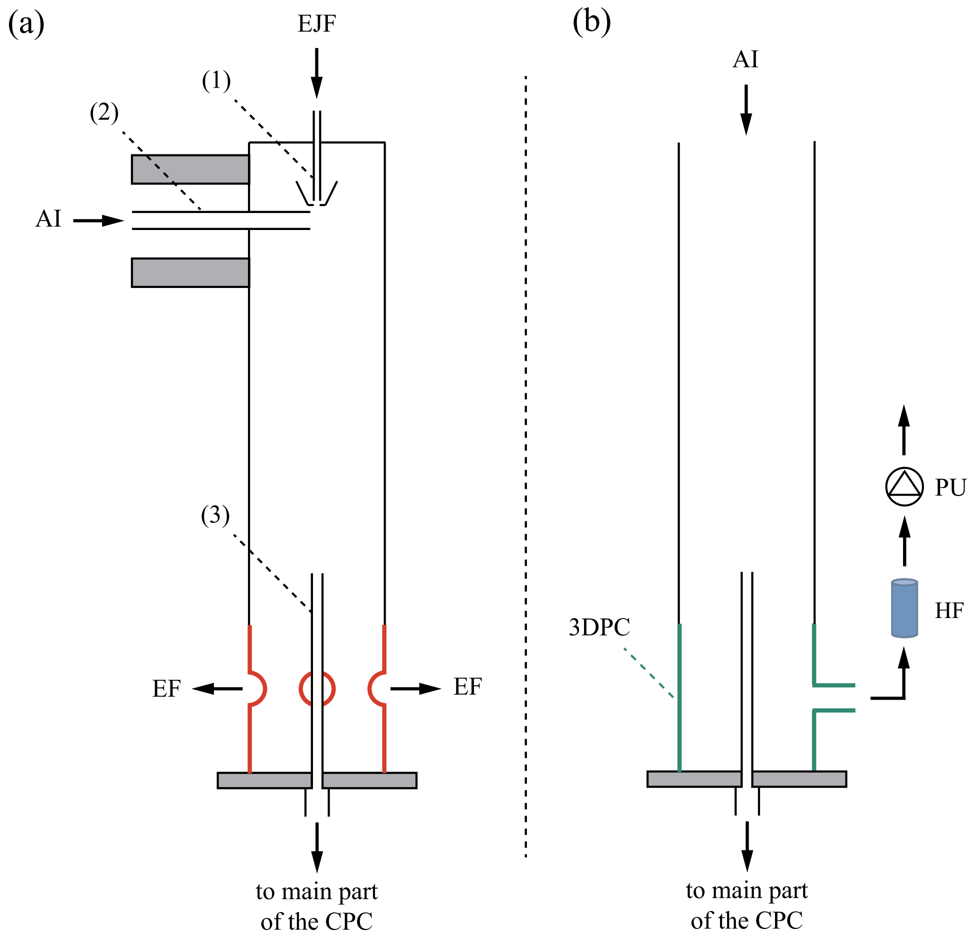

Figure 2. Inlet system of (a) the unmodified, and (b) the modified version of the NAQTS V2000 CPC. The unmodified version includes (1) an ejector diluter, (2) the instrument inlet, and (3) a thin coaxial sampling inlet. In the modified version, the inlet of the instrument including the ejector diluter was removed, and an air-tight 3D-printed T-piece (indicated with green in Figure 2b) was used to replace a part with vent holes (indicated with red in Figure 2a). The 3D-printed T-piece was connected to an external pump for creating a regulated carrier flow. Key: AI: Aerosol Inlet; EJF: Ejector Flow; EF: Excess Flow; 3DPC: 3D Printed Component; HF: HEPA Filter; PU: Pump.

transducers are employed at the high-pressure port of the ejector and at the inlet of the instrument for determining the associated flows and consequently the dilution ratio. We should note again here that the NAQTS V2000 CPC actively controls the temperature of the condenser (set to 18 ± 2 °C) and the saturator (set to 35 ± 2 °C), thus maintaining a constant temperature difference between the two stages.

While the flow system of the NAQTS V2000 CPC is adequate for sampling highly concentrated aerosols (e.g., vehicle emissions, indoor polluted spaces, etc.) as a standalone unit, it creates a very low pressure drop through the inlet of the instrument, and consequently limits its application in places where it needs to be connected downstream aerosol pretreatment stages (e.g., for drying) and sampling lines, and/or other instruments (e.g., a DMA) where significant suction is required. Another potential issue is related to the dilution of the sample flow caused by the ejector, and more specifically to the accuracy of the dilution factor which is calculated based on pressure measurements at different stages of the instrument. While the accuracy of pressure transducers is good (i.e., within ±5%), they can still induce a significant uncertainty when used to determined flow rates within the instrument. In the unmodified unit, two flow rates are important for the calculation of the aerosol number concentration: namely the sample flow, measured by the pressure drop along the sampling inlet, and the dilution flow, measured by the pressure drop along the inlet of the instrument. The combined uncertainty of the two pressure transducers propagates to the calculation of the particle number concentration from the raw counts. When using the modified inlet, only the sample flow is needed for determining the particle number concentration from the raw counts, and thus the resulting uncertainty of the measurement is lower.

For the purpose of characterizing the NAQTS V2000 CPC, but also in view of using the instrument either as a standalone system for characterizing the ambient aerosol (i.e., connected to aerosol sampling and pretreatment lines) or downstream other aerosol equipment (e.g., DMAs) as a detector, we modified its inlet sampling system as illustrated in Figure 2b. In this modification, the instrument inlet and the ejector diluter (cf. parts 1 and 2, respectively, in Figure 2a) were removed. The part of the inlet tubing with the vent holes that surrounds the coaxial thin sampling inlet (i.e., part 3 in Figure 2a) was replaced by a 3D-printed T-piece connected to an external pump as illustrated in Figure 2b. The sampling flow rate remained unchanged compared to the unmodified unit as the internal sampling pump is driven by a controller using differential pressure transducers, in order to measure and control this flow at a preset level. The additional pump increases the flow rate at the inlet of the CPC (i.e., acting as a carrier flow) in order to reduce particle losses in the tubing upstream. In all our tests we kept the carrier flow at a constant value of ca. 1.25 lpm using a critical orifice. The validity of the sample flow measuring system (i.e., based on the differential pressure across the isoaxial thin inlet tube) of the CPC was checked frequently during the experiments with a reference flow meter (Sensidyne, Gilibrator 2, Sensidyne, LP, St. Petersburg, USA).

We should note here that the size-dependent detection efficiency of the standalone and the modified (i.e., when skipping the ejector/dilution system at the inlet) version of the CPC is the same, because the sample flow through the detector remained unaffected in both configurations. In contrast to the detection efficiency, the coincidence error of the CPC is affected by the modification of the inlet. However, considering that the only element of the modification is skipping the dilution, the results from our experiments are directly applicable also to the standalone version of the instrument, proportionally to the dilution factor used that typically ranges from 20 to 50.

Nominally, the NAQTS V2000 air quality monitor communicates *via* Wi-Fi with a browser-based user interface for storing and presenting the recorded measurements every 2–3 s. In order to capture the data with a frequency of 1 Hz, we employed a Universal Asynchronous Receiver/Transmitter (UART) to Universal Serial Bus (USB) converter. This allowed reading the data locally without requiring access to the online web-based user interface.

The Ioner EL 5030 aerosol electrometer employed in our measurements is a sensitive Faraday-cage electrometer having a root mean square (RMS) noise level of 0.5 fA, a zero current of ±1 fA and a resolution of 0.1 fA. In all our measurements we employed a critical orifice coupled to an external pump downstream the electrometer in order to continuously keep the sample flow through it at 1.30 lpm. The sample flow at all stages of the setup (cf. Figure 1) was checked regularly by a Sensidyne Gilibrator 2 and a mass flow meter (TSI, Shoreview, USA; Model 4043).

2.3. Data analysis

The number concentration of the test CPC and the current of the reference electrometer were continuously recorded as described in Sections 2.1 and 2.2.

The reference particle number concentration was determined by the electrometer as:

$$N_{EL} = \frac{I}{neQ}, \tag{1}$$

where I is the current measured by the electrometer, n is the number of elementary charges per particle, e is the electron charge (i.e., 1.6×10^{-19} Cb), and Q is the flow rate passing through the electrometer (i.e., 1.30 lpm). Taking into consideration that the particles used in our tests had diameters that ranged from 9 to 70 nm, as selected by the DMA, we can safely assume that the vast majority was singly charged (Wiedensohler 1988; Bezantakos et al. 2024).

The detection efficiency of the test CPC was determined as the ratio of the number concentration measured by the CPC, N_{CPC}, and that determined by the electrometer, N_{EL}:

$$DE = \frac{N_{CPC}}{N_{EL}}, \tag{2}$$

A simplified two-parameter detection efficiency function (Genrik Mordas et al. 2005) was used to fit the size-dependent detection efficiency measurements as follows:

$$DE\left(d_p\right) = 1 - e^{(a_1 - d_p)/a_2}, \tag{3}$$

Here a_1 is the particle size at which the detection efficiency of the CPC drops to zero (i.e., D_0) and $a_2 = (D_{50} - D_0)/\ln(2)$, where D_{50} is the particle size where the detection efficiency is 50%.

A second-degree polynomial function is used to fit the measured variable in our experiments (i.e., the experimentally measured particle concentrations by the NAQTS V2000 CPC, N_m), capturing the decrease of the detection efficiency with particle concentration due to coincidence. Considering that the NAQTS V2000 CPC measurements have to be corrected to match the reference measurements (i.e., the reference particle concentrations determined by the aerosol electrometer, N_{ref}), the correction function based on this fit can be expressed as:

$$N_{cor} \equiv N_{ref} = aN_m^2 + bN_m + c, \tag{4}$$

where N_{cor}, N_{ref}, and N_m are the corrected (for coincidence), the reference (by the reference electrometer), and measured (by the NAQTS CPC) particle number concentrations, respectively, whereas a, b, and c are fitted parameters. These parameters were obtained by setting N_{cor} to the concentration values measured by the reference aerosol electrometer (i.e., $N_{cor} \equiv N_{ref}$), and fitting Equation (4) to the measurements. To Equations (3) and (4) to the measurements, we employed a non-linear least-square trust-region reflective algorithm based on the interior-reflective Newton method (Coleman and Li 1994, 1996).

The sharpness of the detection efficiency curves was estimated as (Kenny et al. 2004):

$$GSD = \sqrt{{}^{D_{16}}/_{D_{84}}}, \tag{5}$$

where D_{16} and D_{84} represent the particle diameters corresponding to 16% and 84% detection efficiency, respectively.

3. Results and discussion

3.1. Detection efficiency curve

Figure 3 shows the detection efficiency of the NAQTS V2000 CPC as a function of particle mobility diameter. For comparison, the detection efficiency curves of the two commercially available portable CPCs described above, namely of the TSI 3007 and the BMI MCPC 1720 CPCs, are also shown in Figure 3. The curve for the TSI 3007 CPC is generated using the data points of the fitted detection efficiency curve provided by Hameri et al. (2002) while the curve for the Brecthel MCPC 1720 CPC is generated using the equation in Figure 6.1 of the manual of the instrument (BMI 2016). Each point of the NAQTS V2000 CPC detection efficiency curve represents an average value (i.e., derived from ca. 8 min of measurements and Equation (2), while the error bars represent a ±1

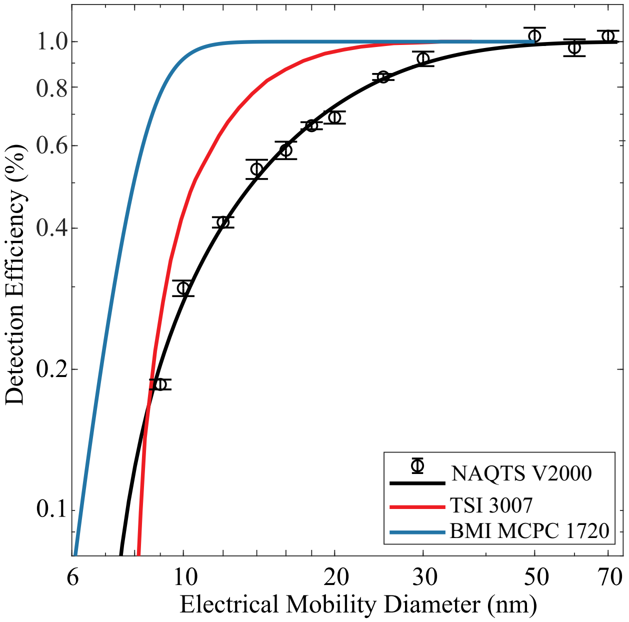

Figure 3. Detection efficiency curves of the NAQTS V2000 CPC (black circles and fitted solid line; measurements carried out in this work), the TSI 3007 CPC (red solid line; based on the measurements reported by Hameri et al. 2002) and the BMI MCPC 1720 (blue solid line; based on the results provided in BMI 2016).

standard deviation). Based on the fitted detection efficiency curve (cf. Equation (3)), the D_{50} and D_{90} values of the tested CPC were determined to be 14 and 30 nm, respectively. In comparison, the TSI 3007 and the BMI 1720 CPCs exhibit a D_{50} of 10.5 and 8 nm, respectively. The D_{50} and D_{90} values of the NAQTS CPC satisfy the current PMP regulations, qualifying this system for vehicle emissions studies.

The detection efficiency of the NAQTS V2000 CPC reaches a plateau of 100% for particles larger than ca. 50 nm. In comparison, the TSI 3007 CPC reaches this plateau for particles larger than 26 nm, whereas the BMI MCPC 1720 CPC for particles larger than ca. 12 nm. The detection efficiency of the NAQTS V2000 CPC is expected to show insignificant differences in performance across various aerosol types, as has already been demonstrated for CPCs such as the TSI 3007 that uses isopropanol as a working fluid (Hameri et al. 2002; Bezantakos and Biskos 2022).

As shown in Figure 3, the detection efficiency curves of the TSI 3007 and the BMI MCPC 1720 CPCs exhibit sharper profiles compared to that of the NAQTS V2000 CPC. More specifically, the sharpness of the curves, estimated by Equation (5), are 0.58 for the NAQTS V2000, 0.75 for the TSI 3007, and 0.84 for the BMI MCPC 1720 CPC. This difference can be attributed to a number of factors, including design characteristics and operating parameters that eventually affect the uniformity of the supersaturated region where the particles activate to droplets, consequently affecting the D_{50} values and the shape/sharpness of the detection efficiency curve. Additionally, diffusional losses of small particles could contribute to the broadening of the detection efficiency curve of the NAQTS V2000 CPC, especially for particles smaller than ca. 15 nm. Furthermore, the absolute temperature difference between the condenser and the saturator, as well as the type of working fluid employed, can affect the activation and growth dynamics of condensation nuclei, thus influencing the overall shape of the curve (Barmpounis et al. 2018; Iida, Stolzenburg, and McMurry 2009).

3.2. Coincidence error

At elevated concentrations, more than one particles can pass through the detection volume of the CPC optical detector simultaneously and counted as one, resulting in an underestimation of their number concentration. As described above, this phenomenon is typically referred to as coincidence error, and can be mitigated either by diluting the sample aerosol (as done in the standalone version of the instrument), and/or by using correction algorithms embedded in the firmware of the instrument.

Figure 4 shows the detection efficiency curve of the modified NAQTS V2000 CPC as a function of particle number concentration. For these measurements we used monodisperse particles having mobility diameters of 60 nm because they can be detected by the CPC with a 100% efficiency as already illustrated in Figure 3. Evidently, underestimation of the particle number concentrations due to coincidence appears at concentrations higher than ca. 10^4 #/cm^3, reducing the detection efficiency to 50% at a concentration of 7×10^4#/cm^3. We should note here that the TSI 3007 and the BMI MCPC 1720 CPCs use coincidence correction factors for measuring the number concentration of aerosol particles up to 10^5 #/cm^3, while retaining their counting accuracies within ±20% and ±8%, respectively (BMI. 2016; Hameri et al. 2002; TSI Inc 2022). In comparison, the number concentration threshold beyond which coincidence error of the NAQTS V2000 CPC appears is similar to that of the first generation of commercial CPCs, such as the TSI 3010 CPC that exhibits coincidence errors at particle concentrations higher than 10^4 #/cm^3 (Quant et al. 1992). Newer CPCs, especially those that employ a sheath flow around the aerosol sample flow (e.g., TSI

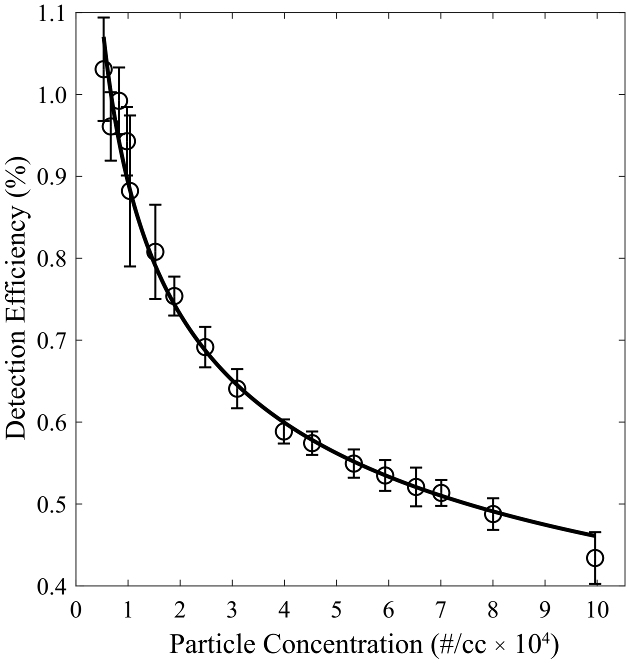

Figure 4. Detection efficiency of the NAQTS V2000 CPC, using the modified inlet, as a function of the reference particle number concentration. The measurements (black circles) were carried out with 60-nm monodisperse particles. The fitted curve is given by $DE(N_{ref}) = 12.61 * N_{ref}^{-0.2875}$, where N_{ref} is the reference particle number concentration.

Model 3786) exhibit significantly higher thresholds, maintaining a counting accuracy within a range of ±10% at particle concentrations up to 10^5 #/cm^3 (Mordas et al. 2008; Quant et al. 1992), or even higher as in the case of the TSI Model 3776 CPC that exhibits accurate detection efficiency at particle concentrations up to 3 x 10^5 #/cm^3 (TSI Inc 2014).

It should be noted here that the firmware of the NAQTS V2000 CPC corrects for the coincidence error. However, the firmware and the coincidence correction algorithm correspond to the original (unmodified) version of the instrument, in which the sample aerosol is significantly diluted at the inlet. In the modified version, the firmware makes a modest correction, i.e., around 4% for particle concentrations below 10^4 #/cm^3 and 10% at 10^5 #/cm^3, as this would correspond to ca. 20–50 times higher concentrations if the system was using the dilution at the inlet as described in the experimental section. Using the NAQTS V2000 CPC without the dilution requires an update of the coincidence correction algorithm for improving its accuracy.

In order to correct for coincidence errors of the modified NAQTS V2000 CPC and expand its applicability for measuring particle number concentrations up to 10^5 #/cm^3, we initially fit Equation (4) to the data collected from the experiments where the concentration of the 60-nm particles was varied (cf. fitted line through the measurements provided in Figure 5). We should note here that the measurements (represented by the black circles) in Figure 5 are average value of the experimental observations, with error bars denoting a ± 1 standard deviation. The black solid line represents Equation (4) with the following fitting parameter values: $\alpha = 2.503\times10^{-5}$, $b = 0.874$, and $c = -122.8$.

The data points represented by the red diamonds are the average coincidence-corrected number concentrations reported by the test CPC after applying Equation (4) against the reference measurements by the electrometer, while the dashed curve is the 1:1 line. The error bars show *a* ± 1 standard deviation of the corrected number concentrations, reflecting measurement uncertainties. The corrected test CPC number concentrations are in agreement within 20% with the reference concentrations.

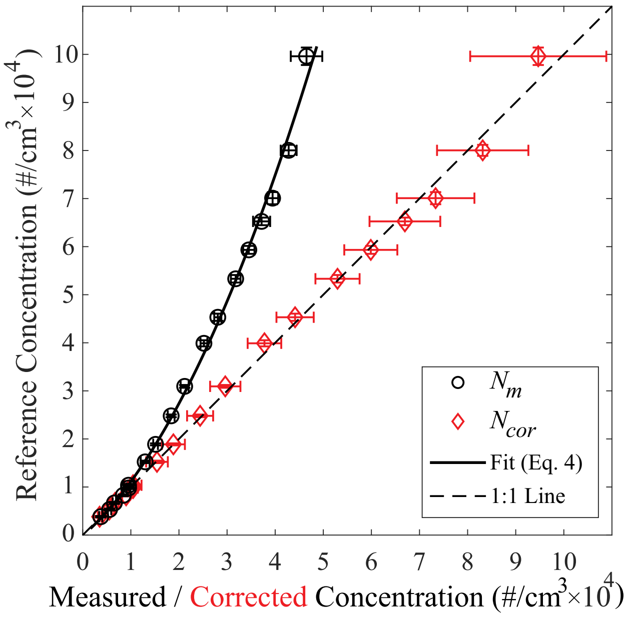

Figure 5. Correlation between as-measured (black circles) and coincidence-error corrected (red diamonds) particle number concentrations by the NAQTS CPC and the reference instrument (Ioner model EL5030 Electrometer). The correction to the measured CPC concentrations is provided by Equation (4) ($N_{cor} \equiv N_{ref} = aN_m^2 + bN_m + c$) with the following fitted parameters: $\alpha = 2.503\times10^{-5}$, $b = 0.874$, and $c = -122.8$.

4. Conclusions

We carried out systematic measurements to determine the detection efficiency and coincidence error of the NAQTS V2000 CPC. The performance of the CPC was evaluated following a modification of its inlet to allow integration in our experimental setup and with other aerosol instrumentation or sampling/treatment lines, but the results apply for its performance also as a standalone instrument without the modification. We show that the CPC exhibits D_{50} and D_{90} values of ca. 14 and 30 nm, respectively, while the detection efficiency reaches 100% for particles larger than 50 nm. With the modification of the inlet we made here, the NAQTS V2000 CPC exhibits negligible coincidence errors for particle number concentrations below 10^4 #/cm^3, while its detection efficiency reduces exponentially, reaching a value of 50% at 7×10^4 #/cm^3. We therefore provide an empirical function for correcting the coincidence error, thus expanding its applicability in environments with particle number concentrations up to 10^5 #/cm^3, while maintaining its counting accuracy within ±20%. When the instrument is used as a standalone device, without modification of its inlet, the applied coincidence correction should kick in at concentrations corresponding to those mentioned above, but corrected for the dilution factor of the sample flow by the ejector pump that typically ranges from 20 to 50. Taken together, our results show that the NAQTS V2000 CPC provides and effective solution for measuring the number concentration of ambient aerosol particles in different environments, and considering its low cost compared to other portable CPCs, it can effectively be employed for distributed observations in field studies.

Data Availability

10.5281/zenodo.10679724.

References

Agarwal, J. K., and G. J. Sem. 1980. Continuous flow, single-particle-counting condensation nucleus counter. *J. Aerosol Sci.* 11 (4):343–57. doi: 10.1016/0021-8502(80)90042-7.

Barmpounis, K., A. Ranjithkumar, A. Schmidt-Ott, M. Attoui, and G. Biskos. 2018. Enhancing the detection efficiency of condensation particle counters for sub-2 nm particles. *J. Aerosol Sci.* 117(March): 44–53. doi: 10.1016/j.jaerosci.2017.12.005.

Bezantakos, S., and G. Biskos. 2022. Temperature and pressure effects on the performance of the portable TSI 3007 condensation particle counter: implications on ground and aerial observations. *J. Aerosol Sci.* 159(January): 105877. doi: 10.1016/j.jaerosci.2021.105877.

Bezantakos, S., C. K. Varnava, R. Papaconstantinou, and G. Biskos. 2024. Performance of the naneos partector 2 multi-metric nanoparticle detector at reduced temperature and pressure conditions. *Aerosol Sci. Technol.* 58 (5): 584–93. doi: 10.1080/02786826.2024.2330471.

BMI. 2016. Model 1720 Mixing Condensation Particle Counter Manual, Ver. 2.2.

Calderón-Garcidueñas, L., A. C. Solt, C. Henríquez-Roldán, R. Torres-Jardón, B. Nuse, L. Herritt, R. Villarreal-Calderón, N. Osnaya, I. Stone, R. García, et al. 2008. Long-Term air pollution exposure is associated with neuroinflammation, an altered innate immune response, disruption of the blood-brain barrier, ultrafine particulate deposition, and accumulation of amyloid β-42 and α-synuclein in children and young adults. *Toxicol. Pathol.* 36 (2):289–310. doi: 10.1177/0192623307313011.

Coleman, T. F., and Y. Li. 1994. On the convergence of interior-reflective newton methods for nonlinear minimization subject to bounds. *Math. Program.* 67 (1-3): 189–224. doi: 10.1007/BF01582221.

Coleman, T. F., and Y. Li. 1996. An interior trust region approach for nonlinear minimization subject to bounds. *SIAM J. Optim.* 6 (2):418–45. doi: 10.1137/0806023.

Finlayson-Pitts, B. J., L. M. Wingen, V. Perraud, and M. J. Ezell. 2020. Open questions on the chemical composition of airborne particles. *Commun. Chem.* 3 (1):108. doi: 10.1038/s42004-020-00347-4.

Giechaskiel, B., T. Lähde, A. D. Melas, V. Valverde, and M. Clairotte. 2021. Uncertainty of laboratory and portable solid particle number systems for regulatory measurements of vehicle emissions. *Environ. Res.* 197 (June): 111068. doi: 10.1016/j.envres.2021.111068.

Hameri, K., I. K. Koponen, P. P. Aalto, and M. Kulmala. 2002. The particle detection efficiency of the TSI-3007 condensation particle counter. *Aerosol Science.*

Harrison, R. M. 2020. Airborne particulate matter. *Philos. Trans. A Math. Phys. Eng. Sci.* 378 (2183):20190319. doi: 10.1098/rsta.2019.0319.

Iida, K., M. R. Stolzenburg, and P. H. McMurry. 2009. Effect of working fluid on sub-2 nm particle detection with a laminar flow ultrafine condensation particle counter. *Aerosol Sci. Technol.* 43 (1):81–96. doi: 10.1080/02786820802488194.

Kenny, L. C., T. Merrifield, D. Mark, R. Gussman, and A. Thorpe. 2004. The development and designation testing of a new USEPA-approved fine particle inlet: a study of the USEPA designation process. *Aerosol Sci. Technol.* 38 (sup2):15–22. doi: 10.1080/027868290502290.

Kim, K.-H., S. A. Jahan, and E. Kabir. 2013. A review on human health perspective of air pollution with respect to allergies and asthma. *Environ. Int.* 59 (September):41–52. doi: 10.1016/j.envint.2013.05.007.

Kousaka, Y., T. Niida, K. Okuyama, and H. Tanaka. 1982. Development of a mixing type condensation nucleus counter. *J. Aerosol Sci.* 13 (3):231–40. doi: 10.1016/0021-8502(82)90064-7.

Lim, S., I. Mudway, N. Molden, J. Holland, and B. Barratt. 2022. Identifying trends in ultrafine particle infiltration and carbon dioxide ventilation in 92 vehicle models. *Sci. Total Environ.* 812 (March):152521. doi: 10.1016/j.scitotenv.2021.152521.

Mavliev, R. 2002. Turbulent mixing condensation nucleus counter. *Atmos. Res.* 62 (3-4):303–14. doi: 10.1016/S0169-8095(02)00016-9.

McMurry, P. H. 2000. The history of condensation nucleus counters. *Aerosol Sci. Technol.* 33 (4):297–322. doi: 10.1080/02786820050121512.

Molden, N., C. Hemming, F. Leach, J. G. Levine, K. Ropkins, and W. Bloss. 2023. Exposures to particles and volatile organic compounds across multiple transportation modes. *Sustainability* 15 (5):4005. doi: 10.3390/su15054005.

Mordas, G., M. Kulmala, T. Petäjä, P. P. Aalto, V. Matulevičius, V. Grigoraitis, V. Ulevičius, V. Grauslys, A. Ukkonen, and K. Hämeri. 2005. Design and performance characteristics of a condensation particle counter UF-02proto. *SustainabilityBoreal Environ. Res.* 10:543–52.

Mordas, G., H. E. Manninen, T. Petäjä, P. P. Aalto, K. Hämeri, and M. Kulmala. 2008. On operation of the ultra-fine water-based CPC TSI 3786 and comparison with other TSI models (TSI 3776, TSI 3772, TSI 3025, TSI 3010, TSI 3007). *Aerosol Sci. Technol.* 42 (2):152–8. doi: 10.1080/02786820701846252.

NAQTS. 2019. NAQTS V2000 operations manual,Ver 2.11.

Neuberger, M., M. G. Schimek, F. Horak, H. Moshammer, M. Kundi, T. Frischer, B. Gomiscek, H. Puxbaum, and H. Hauck. 2004. Acute effects of particulate matter on respiratory diseases, symptoms and functions. *Atmos. Environ.* 38 (24):3971–81. doi: 10.1016/j.atmosenv.2003.12.044.

Ohlwein, S., R. Kappeler, M. Kutlar Joss, N. Künzli, and B. Hoffmann. 2019. Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence. *Int. J. Public Health* 64 (4):547–59. doi: 10.1007/s00038-019-01202-7.

Quant, F. R., R. Caldow, G. J. Sem, and T. J. Addison. 1992. Performance of condensation particle counters with three continuous-flow designs. *J. Aerosol Sci.* 23 (January):405–8. doi: 10.1016/0021-8502(92)90435-X.

Rai, P. K. 2016. Impacts of particulate matter pollution on plants: implications for environmental biomonitoring. *Ecotoxicol. Environ. Saf.* 129 (July):120–36. doi: 10.1016/j.ecoenv.2016.03.012.

Rosenlund, M., F. Forastiere, D. Porta, M. De Sario, C. Badaloni, and C. A. Perucci. 2009. Traffic-Related air pollution in relation to respiratory symptoms, allergic sensitisation and lung function in schoolchildren. *Thorax* 64 (7):573–80. doi: 10.1136/thx.2007.094953.

Terres, A., V. Ebert, A. Nowak, J. Rosahl, M. Hildebrandt, J. Southgate, I. Marshall, A. Mamakos, M. Cresnoverh, S. Usarek, et al. 2018. *Particle measurement programme (PMP) – inter-laboratory correlation exercise with condensation particle counters (CPCs).* EUR 29277 EN. Luxembourg: Publications Office of the European Union. doi: 10.2760/859241.

Thurston, G. D., H. Kipen, I. Annesi-Maesano, J. Balmes, R. D. Brook, K. Cromar, S. De Matteis, F. Forastiere, B. Forsberg, M. W. Frampton, et al. 2017. A joint ERS/ATS policy statement: what constitutes an adverse health effect of air pollution? an analytical framework. *Eur. Respir. J.* 49 (1):1600419. doi: 10.1183/13993003.00419-2016.

TSI Inc. 2014. Model 3776 ultrafine condensation particle counter operation and service manual, Rev.J.

TSI Inc. 2022. Model 3007 hand-held condensation particle counter data sheet, 5001117, Rev.D.

Wang, J., V. F. McNeill, D. R. Collins, and R. C. Flagan. 2002. Fast mixing condensation nucleus counter: application to rapid scanning differential mobility analyzer measurements. *Aerosol Sci. Technol.* 36 (6):678–89. doi: 10.1080/02786820290038366.

Whitby, K. T., and W. E. Clark. 1966. Electric aerosol particle counting and size distribution measuring system for the 0.015 to 1 μ size range. *Tellus* 18 (2-3):573–86. doi: 10.1111/j.2153-3490.1966.tb00272.x.

Wiedensohler, A. 1988. An approximation of the bipolar charge distribution for particles in the submicron size range. *J. Aerosol Sci.* 19 (3):387–9. doi: 10.1016/0021-8502(88)90278-9.