Technical note

Performance of a venturi dilution chamber for sampling 3–20 nm particles

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Abstract

The transmission efficiency of a venturi mixing and dilution system was investigated with laboratory generated aerosol by comparison of two condensation particle counters (CPCs). The transmission efficiency exceeded 95% for particle sizes between 3 and 20 nm. The use of the diluter system is demonstrated through comparison with total concentrations derived from a nano-scanning mobility particle sizer (nSMPS) applied to measuring a rapidly changing atmospheric nucleation mode. The study indicates that the diluted-CPC sampler can resolve rapidly changing, and more intense peaks in excess of $10^6$ cm$^{-3}$, which are otherwise missing or under-sampled by the nSMPS.

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1. Introduction

In terms of measuring total particle number concentrations during nucleation bursts, the most commonly used particle counter is the TSI 3025 which counts particles between 3 nm (50% cut size) and $\sim 1$ μm. This instrument is, however, limited to concentrations below $10^5$ cm$^{-3}$ and consequently, is unsuitable for characterising intense nucleation or nano-particle systems leading to concentrations of the order of $10^6$ cm$^{-3}$ or higher (O’Dowd et al., 2002). A nano-scanning mobility particle sizer (nSMPS) can easily operate correctly at these high concentrations. However, the scanning time is typi-
cally limited to 30–60 s and thus cannot capture micro-scale details during these events. Consequently, to achieve the measurement capability of very high particle concentrations, while maintaining a high temporal response of 1 Hz as associated with the TSI 3025, the aerosol system being sampled will require dilution.

A number of different approaches are taken to dilute aerosol samples. These include for example: the cavity-type diluter which captures a fixed volume of aerosol into a cavity before mixing with particle free air; the venturi-type which operates by drawing a known fraction of particle free sheath air to mix with an aerosol sample; and a capillary-type diluter which uses an aerosol capillary to dilute with filtered air from the original air sample. These systems have been tested by Hueglin, Scherrer, and Burtscher (1997) and Helsper, Mölter, and Heller (1990), respectively, and were all found to perform well. However, some of the more typical capillary systems suffer from high diffusion losses for the smallest nanometer sized particles and thus are not suitable for studies in the nano-particle size range.

In this study, we test a dilution system which can operate with minimal losses, particularly for nanometer sized particles, and at dilution ratios of the order of 10–20. The type of dilution chamber selected is a modified version of the venturi-type dilution chamber designed by Koch, Lodding, Molter, and Munzinger (1988). The original design has undergone previous calibration by Helsper et al. (1990), for particle sizes of 0.1–10 μm. Cheng, Storey, Wainman, and Dam (2002) also showed no discernible difference in dilution efficiency for solid particles of the same particle diameter range, however, they did note some differences for chemical species leading to liquid drops rather than solid particles. Such a dilution system is commercially available in the form of the as Palas® VKL-10 system and Dekati® ejector diluter. In these systems, the dilution ratio is typically determined by the manufacturer.

The dilution system studied here differs from the aforementioned system in two ways: (1) the dilution flow is a user-selectable, set by a critical orifice, and operated in a closed-loop; (2) The inlet nozzle is adjustable to provide balanced flow with the aerosol-detector. This modified venturi-dilution system’s performance is evaluated for the transmission efficiency of nano-particle aerosols with sizes between 3–20 nm.

2. Theory and dilution-chamber design

The cross-section and dimensions of the dilution chamber used in this experiment is shown in Fig. 1. In normal operation, or open-loop configuration, the velocity of the incoming particle free dilution flow results in an under pressure, drawing aerosol flow in through the inlet nozzle and the mixing of the combined flows in the mixing chamber causes the dilution. The relationship between pressure and flow velocity is governed by the Bernoulli equation: $p + \rho v^2/2 + \rho g y = c$ where $p$ is the pressure, $\rho$ is the density, $v$ is the velocity, $g$ is acceleration due to gravity, $y$ is height above a reference level and $c$ is a constant.

The height refers to the annular gap determined by the position of the inlet nozzle (see Fig. 1). By adjustment of the inlet nozzle position, the dilution ratio changes as the height $y$ is changed, since the aerosol velocity drawn into the chamber is also changed accordingly. If no pressure difference is found between the annular nozzle region and the mixing area of the chamber, the dilution factor can be determined by the inlet nozzle diameter and the annular gap distance, $y$. The annular gap is set to a fixed position to optimise dilution and the dilution factor ($W$) can be defined as the sum of total air flow (dilution + sample air) divided by the incoming aerosol flow.
The target particle concentration upper limit to measure with minimal losses was $10^6 \text{ cm}^{-3}$, thus, a concentration ratio of 15–20 was sought. The dilution flow rate determines the amount of dilution since the TSI CPC 3025 aerosol detector sample flow of $1.51 \text{ min}^{-1}$ is fixed and a critical-orifice was configured to maintain this constant excess airflow, and thus defines the closed-loop dilution flow. A similar closed-loop flow arrangement is used for the differential mobility analyser (DMA) sheath/excess flow and is described by Jokinen and Makela (1997). To avoid moisture accumulation in the dilution chamber under high humidity conditions, the closed-loop system flow comprises re-circulating dried dilution air using a diaphragm pump and inline vapour scrubber. For the studies presented here, the condensation particle counter (CPC) was operated in high-flow mode resulting in a sample flow of $1.51 \text{ min}^{-1}$ and the dilution flow was set to $24.61 \text{ min}^{-1}$, leading to a dilution ratio of 17.4 according to flow considerations only.

3. Experimental results

The determination of the transmission efficiency of the dilution chamber involved a two-stage experiment. The first stage inter-calibrated two TSI CPC 3025’s for particle number concentration counting efficiency as a function of size. For this stage, nichrome particles were generated using a heated wire and were classified using a nano-electrostatic classifier. The schematic outline of the experimental setup is illustrated in Fig. 2. For stage 1 of the experiment, the dilution system was omitted. The electrostatic classifier was operated with a 10:1 (15 : $1.51 \text{ min}^{-1}$) sheath to sample flow ratio and thus generated a monodisperse size distribution with an accuracy of ±5%. A range of monodisperse distributions were generated between 3 and 20 nm. This experiment produced a CPC calibration efficiency which has to be introduced for all studies involving these two particular CPCs.

For the second stage, the dilution chamber was introduced into the experimental configuration as outlined in Fig. 2 and a range of monodisperse aerosol distributions between 3 and 20 nm was again generated and transmitted to both the diluted and non-diluted CPCs in parallel. This produces, in combination with the dilution ratio and CPC calibration efficiency, the transmission efficiency function for sizes below 20 nm.
Fig. 2. Schematic layout of experimental setup for laboratory experiments.

Fig. 3. CPC cross calibration efficiency and dilution system transfer function for particles between 3.5 and 20 nm.

Results from the CPC intercomparison study determined that the inter-calibration efficiency was 95% for sizes larger than 5 nm, falling to 86% at 3 nm (Fig. 3). This CPC calibration efficiency factor was applied to normalise the concentrations, as a function of size, for the second stage. For the second stage of the experiment, the dilution efficiency was found to be typically greater than 93% for all sizes tested, with the lowest efficiency occurring for the smallest particles (Fig. 3).
4. Evaluation of dilution chamber during coastal nucleation events

The diluted system, coupled to a 3025 CPC was deployed at the Mace Head atmospheric research station where concentrations in excess of $10^6 \text{ cm}^{-3}$, resulting from intense nucleation events, are regularly encountered (O'Dowd et al., 2002). Its performance at determining particle concentration during these events was evaluated through comparison of total particle concentration determined by a TSI nSMPS. The nSMPS size range was limited to 3.5–15 nm, however, this captures most of the particles contributing to total concentration during such events as the majority of particles reside at sizes smaller than 15 nm (O'Dowd et al., 2002). The nSMPS data was chosen for comparison since, due to the charging efficiency of nano-particles, only a small fraction of the aerosol is transmitted and thus, avoids saturation in the CPC, and it provides the fastest time response (20 s) for comparison with the dilution-chamber CPC.

The CPC data were corrected for the flow dilution ratio ($W = 17.4$) and a 95% transmission efficiency was then applied to arrive at the corrected concentration. This concentration is then averaged up to 20 s averages for comparison with the total concentration derived from the nano-SMPS. The comparison of the two systems during a coastal nucleation event is shown in Fig. 4 where both a comparison of the CPC
concentration integrated over the 20 s scan time for the nSMPS and the SMPS is shown along with the comparison of the 1 Hz CPC data with the nSMPS.

The agreement on the 20 s timescale is quite good throughout the experiment although the higher integrated concentrations seen by the CPC illustrates that the nSMPS is missing some peaks during its scan sequence. Further, the 1 Hz CPC data reveal notably higher peak concentrations when compared to the nSMPS, in many cases, more than a factor of two. While part of the difference can be attributed to the 3 nm size cut in the CPC compared to the 3.5 nm cut in the nSMPS, the majority of the difference relates to the improved ability of the diluted-CPC to resolve very high concentrations over very short timescales compared to the resolution of the nSMPS. Overall, this exercise demonstrates that the dilution chamber coupled to the TSI 3025 CPC provides an effective way to measure total particle concentration at sizes larger than 3 nm in a rapidly changing aerosol system.

5. Conclusion

The performance of a venturi-type dilution system for aerosol concentrations in excess of $10^6 \text{ cm}^{-3}$ was evaluated during laboratory studies and it was found that the transmission efficiency for particles between 3 and 20 nm was at least 95%. The dilution system was operated at a dilution ratio of 17.4 and the system was applied to a rapidly changing and nucleating atmospheric aerosol under natural conditions. The coupled dilution chamber and CPC provided an effective way to capture rapidly changing features of a rapidly changing aerosol system at concentrations of up to $1.8 \times 10^6 \text{ cm}^{-3}$ residing in the 3–20 nm size range.

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