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Technical note

Particle counting efficiencies of new TSI condensation particle counters

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Abstract

In this study calibration measurements of new TSI condensation particle counter models, using either butanol or water as working fluid, are described. Experiments were carried our at ambient, laboratory conditions for two particle materials, silver and sodium chloride. The obtained counting efficiency curves are presented.

Keywords: Condensation particle counter (CPC); Counting efficiency

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1. Introduction

Condensation particle counters (CPCs) are widely used for measurements of airborne particles (cf. Baron & Willeke, 2001). In 2004, a family of water-based CPCs (WCPCs) was introduced by TSI (TSI Inc., St Paul, MN, USA, cf. Hering, Stolzenburg, Quant, Oberreit, & Keady, 2005), the models 3782, 3785, and 3786. Also, in 2005, a new generation of butanol CPCs was presented by this company (CPCs 3772, 3775, and 3776). Since TSI discontinued manufacturing of the previous CPC models, these new instruments are going to replace the older instruments in the field within the next few years. In 2006, Petäjä et al. published first calibration measurement results for the WCPC 3785 and three different particle materials. In this study, we present counting efficiencies of two WCPC models (3785 and 3786) and three CPC pre-production models (3772, 3775, and 3776) in the size range from 3 to 40 nm. Calibration runs were carried out for two aerosol materials, silver (Ag) and sodium chloride (NaCl), at IFT laboratory during four days in January 2006.

2. Experimental

The set-up used for the CPC calibration is shown in Fig. 1. Polydisperse silver aerosol was generated in a tube furnace at temperatures of 910–1100 °C according to Scheibel and Porstendörfer (1983). After applying dry quench air, the newly formed particles were sintered in a second furnace at 450–500 °C in order to achieve closed-packed, nearly

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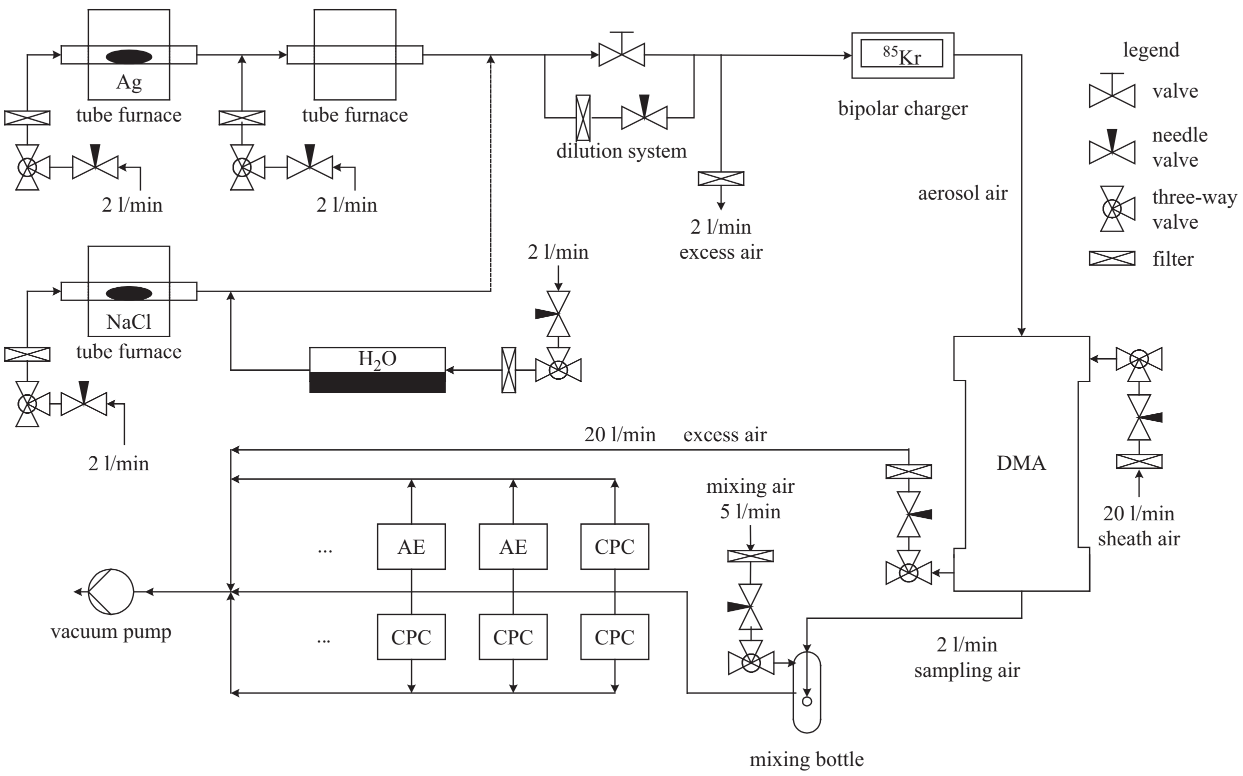

Fig. 1. CPC calibration set-up.

spherical particles (Ku & Maynard, 2006). Alternatively, a third furnace was used to generate sodium chloride particles. The respective furnace temperature was chosen between 470 and 570 °C and humidified quench air (RH $\approx$ 100%) of equal flow rate as the aerosol flow was used. Consequently the relative humidity of the sodium chloride aerosol flow should have been around 50%. In previous own experiments and also by other groups (e.g., Krämer, Pöschl, & Niessner, 2000), it was observed that sodium chloride particles can change their structure and hence their size when encountering gaseous water even far below the deliquescence point (75–90%). In order to force this change or shrinking process to take place before the particles enter the DMA, we humidified the aerosol.

Downstream of the furnaces, a dilution system was used to keep the particle number concentration at the CPCs between 1000 and 4000 particles/cm^3. This range was chosen in order to have a good signal to noise ratio at the reference electrometers and to minimize coincidence effects in the CPC optics. After dilution, the aerosol particles were charged in an ^{85}Kr bipolar charger and a monodisperse fraction was selected by a differential mobility analyzer (DMA, Vienna-type, short: $L = 11$ cm, $r_{\text{in}} = 2.5$ cm, $r_{\text{out}} = 3.35$ cm). The sheath and excess air flow rates of the DMA were adjusted to 20 l/min, the aerosol and sampling flow rates were set to either 2 or 3 l/min. Downstream of the DMA, the monodisperse aerosol was diluted with particle-free air in a mixing bottle to achieve the required total flow rate for the particle counters and two reference aerosol electrometers (TSI 3068B and IFT home-made). Individual flow rates were 1.0, 1.5, and 1.5 l/min for the three CPCs 3772, 3775, and 3776, respectively. The WCPCs had flow rates of 1.035 (WCPC 3785) and 0.600 (WCPC 3786), respectively. Electrometer flow rates were chosen to be either 1.5 or 3.0 l/min. The individual instruments were fed from a 2 m long tube header with 11 ports downstream the mixing bottle. Sampling lines from the header to the instruments were arranged in a symmetric pattern with one large 45° bend and a 40 cm straight line each.

Two data acquisition systems were used simultaneously in order to record the readings of the instruments. The first one was a multifunction data acquisition card in a PC controlled with LabVIEW, which read the analog voltage signal from the IFT electrometer and the pulse outputs from up to eight CPCs. In order to get a pulse output from the WCPCs, we modified the BNC ports of these instruments as described in the TSI application note

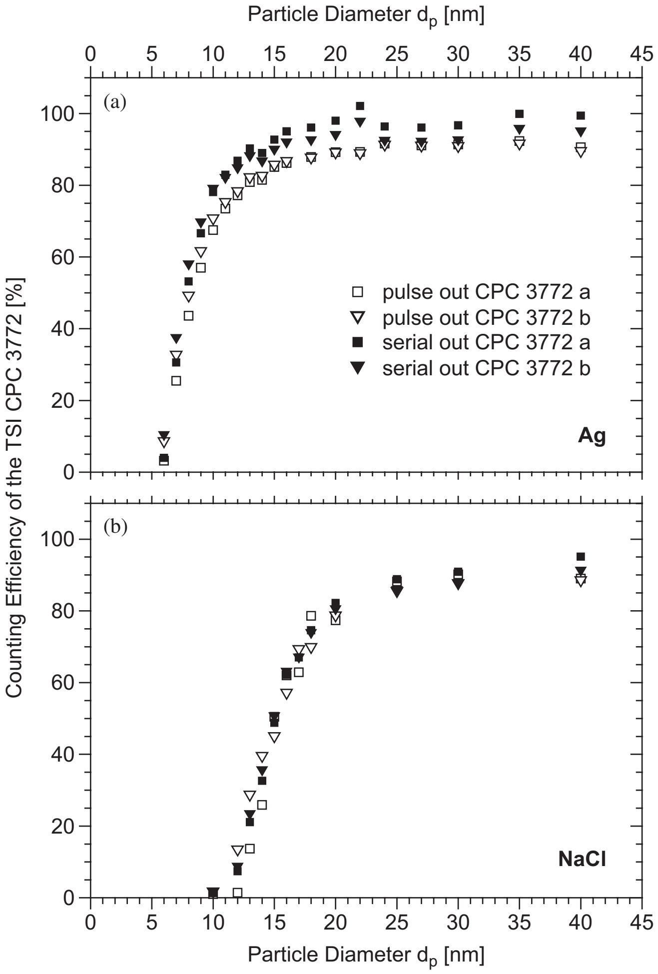

Fig. 2. CPC 3772 counting efficiencies for (a) silver and (b) sodium chloride particles. Displayed are the mean values of least two calibration runs per CPC. Pulse outputs were recorded by the IFT data acquisition system (counter card, LabVIEW) whereas particle signals from serial ports (RS232) were measured by TSI's Aerosol Instrument Manager software.

"WCPC-002" (cf. http://www.tsi.com/documents/WCPC-002-A4.pdf). Note that in this configuration the respective particle signals are not live-time corrected, as it is normally the case for the WCPCs. The second data acquisition system consisted of TSI's Aerosol Instrument Manager software running on a laptop computer that recorded particle concentrations directly via the serial RS232 ports of the CPCs and the TSI 3068B electrometer. As the pulse output from the CPCs collected by the IFT data acquisition card corresponds to raw counts, corrections for coincidence, data acquisition system uncertainty, and diffusion losses in the sampling lines were applied to the data. Coincidence was corrected with the respective equation given in Hermann and Wiedensohler (2001), using coincidence constants determined during the workshop. Therefore, the DMA was set to 24 nm and the concentrations registered by the CPCs were compared to the electrometer readings for at least 12 concentrations in the range between 500 and 15,000 particles/cm^3.

The data acquisition uncertainty originated from the inaccuracy of the software timing of the LabVIEW program when running eight counters in parallel. Again this effect could be corrected for by conducting additional measurements. Diffusional losses in the individual sampling lines where calculated according to the equations 19–20 and 19–21 given in Baron and Willeke (2001) using the above flow rates. The particle concentrations collected by the TSI software were already corrected for coincidence in the instruments so only a diffusion loss correction was applied in the data processing.

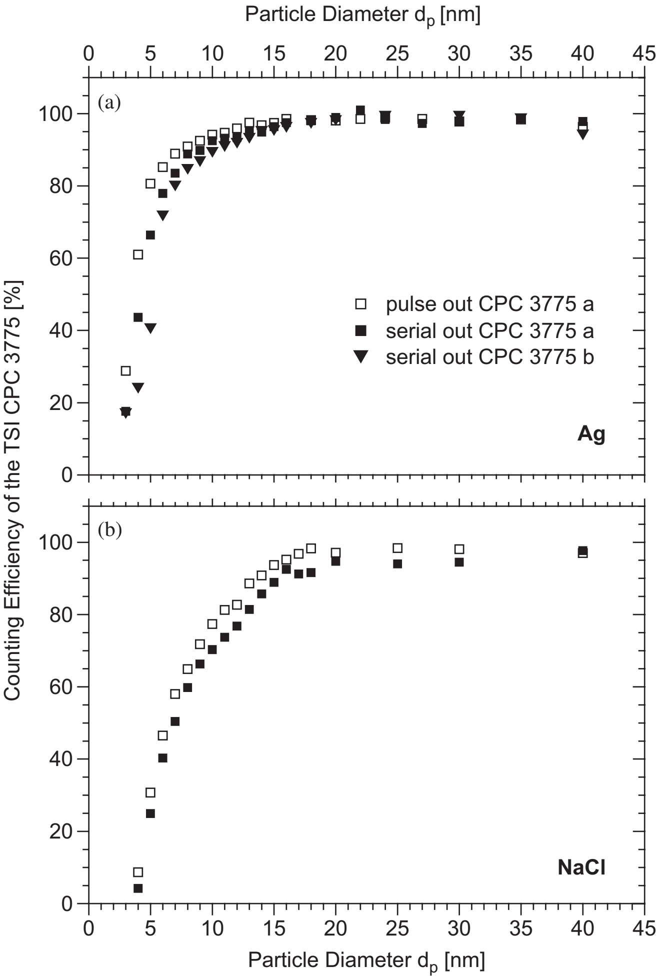

Fig. 3. CPC 3775 counting efficiencies for (a) silver and (b) sodium chloride particles.

The electrometer data were corrected for background offset, measured regularly between the particle measurements. Furthermore, as the two electrometers had different geometries, and diffusional losses for particles smaller than 10 nm were non-negligible for the IFT electrometer, a correction function was applied to the IFT electrometer data. This function was simply the ratio of the two electrometer readings. Above 20 nm the two instruments agreed within less than 4%. The CPC particle counting efficiency η was finally calculated as the ratio of the corrected CPC and electrometer particle number concentrations at each individual particle diameter. Thereby, two counting efficiency data sets were obtained, one referring the serial output data to the TSI electrometer data, and the second referring the pulse output data to the IFT electrometer. For each CPC model, two counters were calibrated except for the WCPC 3785 due to time limitations. In the course of the experiment it turned out that for the model 3776 the counting efficiencies measured via the pulse output were systematically too low. A modification of the pulse out connector performed by TSI after the workshop now guarantees an agreement of the serial and the pulse output within 3%. For the workshop data of the 3776, we applied a constant correction factor of about 10% to the pulse output data, which was determined as the ratio of pulse output to the serial output for the mean counting efficiency for 30 and 40 nm.

3. Results and discussion

The counting efficiencies obtained for the individual butanol-based CPC models are shown in Figs. 2–4. Displayed are mean values of at least two calibration runs. For the sake of clarity error bars are not displayed, but account for

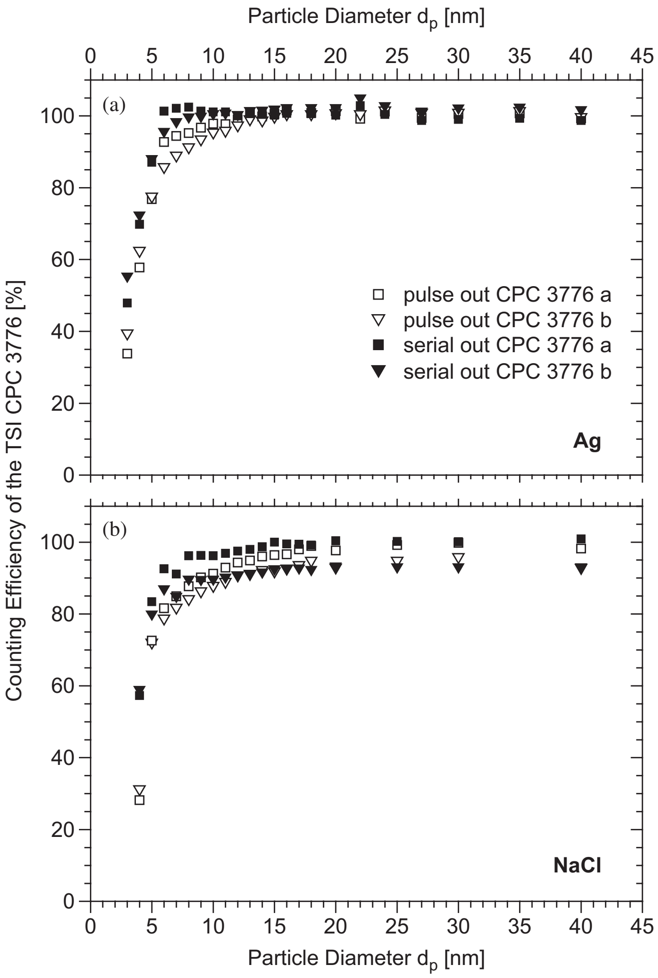

Fig. 4. CPC 3776 counting efficiencies for (a) silver and (b) sodium chloride particles.

approximately ±0.3–1.3 nm (or ±2–10% in particle diameter, d_p) on the x-axis, representing one sigma of the DMA transfer function according to Stolzenburg (1988). Y-axis uncertainties typify the experimental standard deviation of the mean values and are mostly below 4% (absolute values) in the part of the counting efficiency curve where it levels out (to the right). In the slope, however, uncertainties can be much higher, up to 20%. The results for the WCPCs are shown in Fig. 5. For the two models WCPC 3785 and WCPC 3786 only calibration with silver particles was carried out because there was no time left for a calibration with sodium chloride particles. Silver was chosen because it is hydrophobic and hence it is more difficult to activate in a WCPC. The response of the WCPCs to sodium chloride should be even better.

The counting efficiency curves for the CPC models 3772 and sodium chloride particles obtained with two different data acquisition systems agree very well (Fig. 2(b)). However for silver, the counting efficiencies measured using the pulse output were always lower by 2–10% compared to the serial output, but mostly agree within the experimental errors. As both materials were measured on the same days, a reason for that discrepancy originating from the set-up is unlikely. Other reasons are discussed below.

The CPC 3775 curves are displayed in Fig. 3. In the upper figure, the data for the second CPC (b) and its pulse output are missing, since this pulse output was not working properly during the experiment (all CPC pulse outputs were tested with an oscilloscope in the course of the workshop). For both materials the curves agree very well within the experimental errors. The same holds true for the models 3776 after applying the correction mentioned in the experimental section (Fig. 4). The serial output data seem to yield a slightly steeper slope compared

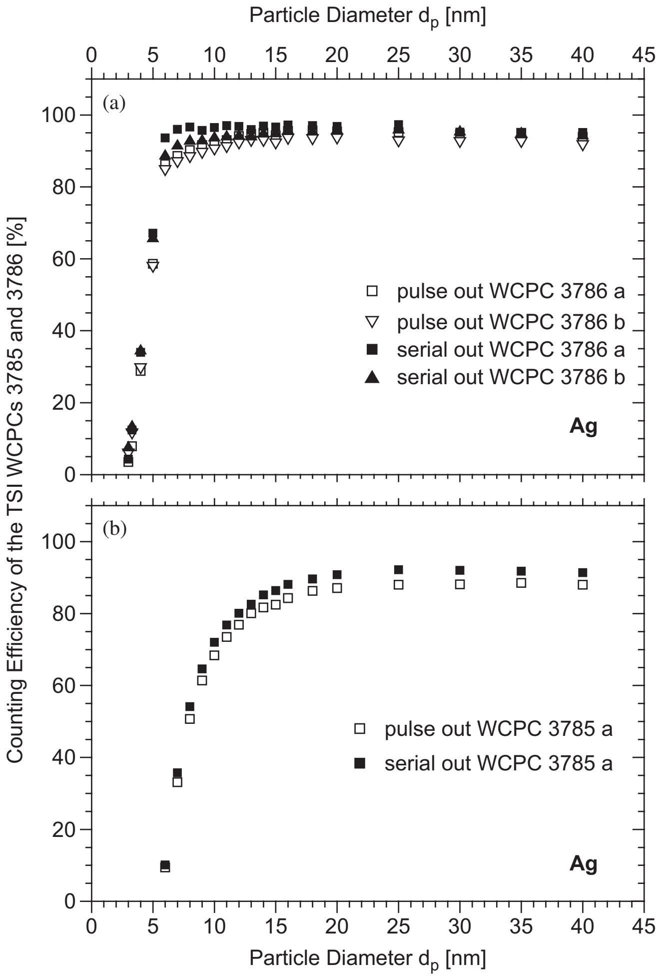

Fig. 5. Counting efficiencies for WCPC 3785 (b) and WCPC 3786 (a) for silver particles.

to the pulse output data. Differences between the two recording methods of up to 10% still lie within the experimental errors. The counting efficiencies for the WCPCs 3785 and 3786 and silver particles are shown in Fig. 5. Although the pulse output data are generally lower than the serial output they still agree within the experimental uncertainties.

To facilitate a comparison between the different CPC models, the mean counting efficiency over all available curves for each CPC type (pulse output as well as serial output) and particle material was calculated. This was done although the differences between the pulse and the serial output are not fully understood. The different data evaluation procedures could not have had an influence, because this would not explain the sometimes good and sometimes bad agreement. In principle it is possible, that the aerosol particles were not distributed spatial homogeneously in the tube header, leading to two different electrometer readings and hence different counting efficiencies. However, comparing the electrometers yielded a maximum deviation of individual measurements from the used ratio correction function of 4%, mostly only 2%. Hence, this could only partly explain the observed differences. In lack of knowledge, which data set is the more correct one, it was decided to use both for the calculation of the mean counting efficiency. The resulting curves were fitted using a four-parameter exponential function (Eq. (1)) given by Wiedensohler et al. (1997):

$$\eta = a - b \cdot \left(1 + \exp\left(\frac{d_p - d_1}{d_2}\right)\right)^{-1} \quad \text{for } d_p \geqslant d_0, \tag{1}$$

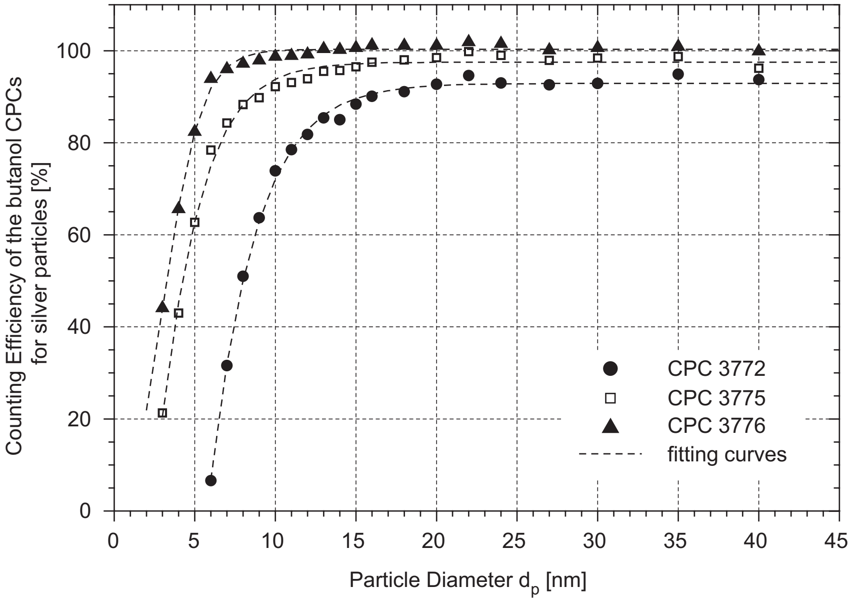

Fig. 6. Mean counting efficiency curves for the CPCs and silver particles.

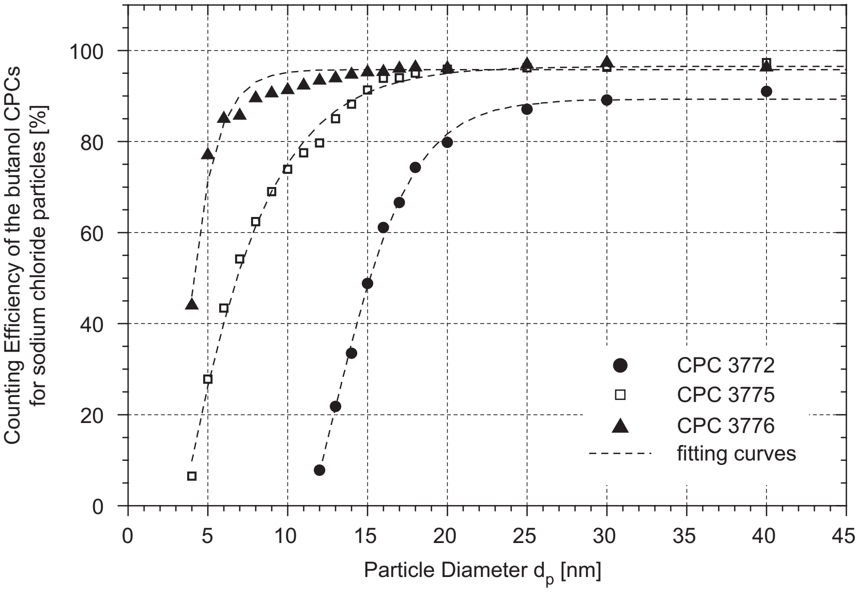

Fig. 7. Mean counting efficiency curves for the CPCs and sodium chloride particles.

$$\eta = 0 \quad \text{for } d_p < d_0, \tag{2}$$

$$\text{with} \quad d_0 = d_2 \cdot \ln\left(\frac{b}{a-1}\right) + d_1. \tag{3}$$

The respective data points and curves are displayed in Figs. 6–8. With the help of this empirical approach, the diameters of the 50% particle detection efficiency, d_{p50}, were calculated. In this context, the d_{p50} was defined as particle diameter where the counting efficiency reaches half the maximum asymptotic counting efficiency. The fitting parameters as well as the d_{p50} values are listed in Table 1.

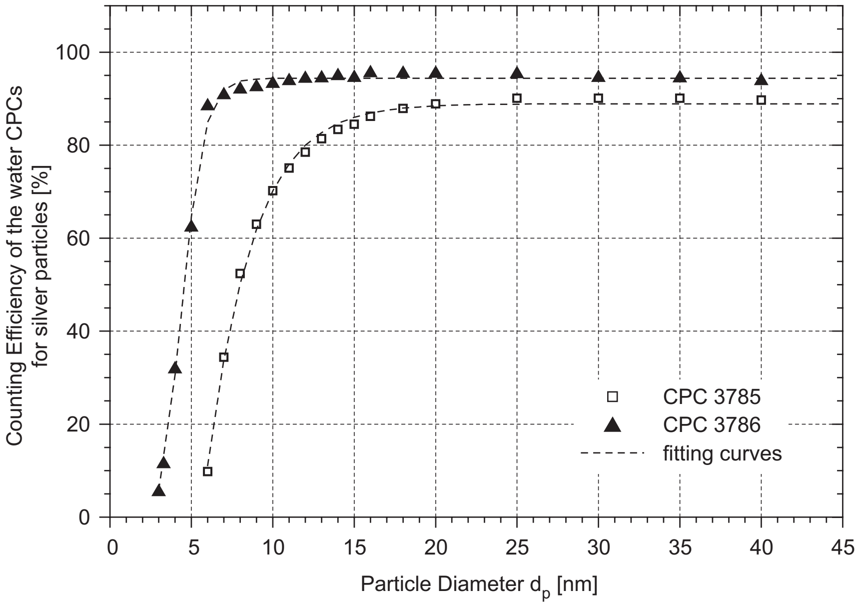

Fig. 8. Mean counting efficiency curves for the WCPCs and silver particles.

Table 1
Fit parameters a, b, d_1, and d_2 as well as the 50% detection diameter d_{p50} of the mean (W)CPC counting efficiency curves

(W)CPC	Particle material	a	b	d_1 (nm)	d_2 (nm)	d_{p50} (nm)
3772	Ag	0.929	8.958	0	2.674	7.8
3772	NaCl	0.893	1.480	12.554	2.554	14.7
3775	Ag	0.975	3.855	0	2.158	4.2
3775	NaCl	0.965	3.431	0	3.683	6.7
3776	Ag	1.003	1.107	3.044	1.185	3.3
3776	NaCl	0.958	10.002	0	1.355	4.1
3785	Ag	0.889	8.185	0	2.663	7.6
3786	Ag	0.994	1.014	4.375	0.712	4.4

Values are calculated according to Eq. (1).

For the WCPC 3785, Petäjä et al. (2006) performed similar calibration measurements using Ag, NaCl, and $(NH_4)_2SO_4$ particles. The d_{p50} obtained for Ag was 5.8 nm, which is lower than the 7.6 nm from this study. However, as already shown by Hering et al. (2005), small hydrophilic impurities on hydrophobic particles can lead to strong changes in the counting efficiency curves. Hence, it is well possible that slightly different WCPC threshold diameters can be caused by different set-ups. Clearly further experiments are required in order to resolve the sometimes observed discrepancy between the serial and the pulse output. Furthermore, a better statistics as well as measurements with additional particle materials are desirable.

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