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Discussions

Characterization of three new condensation particle counters for sub-3 nm particle detection: ADI versatile water CPC, TSI 3777 nano enhancer and boosted TSI 3010

Juha Kangasluoma[1], Susanne Hering[2], David Picard[3], Greg Lewis[2], Joonas Enroth[1], Frans Korhonen[1], Markku Kulmala[1], Karine Sellegri[3], Michel Attoui[1,4], Tuukka Petäjä[1]

[1] Department of Physics, P.O. Box 64, 00014, University of Helsinki, Helsinki, Finland
[2] Aerosol Dynamics Inc., Berkeley, CA, USA
[3] Laboratoire de Météorologie Physique, UMR6016, Observatoire de Physique du Globe de Clermont-Ferrand, CNRS – Université Blaise Pascal, Clermont-Ferrand, France
[4] University Paris Est Creteil, University Paris-Diderot, LISA, UMR CNRS 7583, France

Abstract

The scientific need to understand nanoparticle dynamics at sizes below 3 nm has pushed companies to develop commercial solutions to measure particles down to 1 nm. In this study we characterize the performance of three new particle counters able to detect particles smaller than 3 nm: Aerosol Dynamics Inc versatile water condensation particle counter (v-WCPC, ADI, Berkeley, USA), TSI 3777 nano enhancer (TSI Inc., Shoreview, USA) and modified and boosted 3010 type CPC from Clermont Ferrand University called as B3010. The 3777 and v-WCPC were characterized using tungsten oxide test particles with all charging states: negative, positive and neutral, and with positively charged tetradodecylammonium bromide. The detection efficiencies of the particle counters were measured with two different temperature settings: low temperature difference settings so that the CPCs did not detect any ions from a radioactive source; and high temperature difference settings so that the supersaturation was at the onset of homogeneous nucleation for the 3777, or confined within the range of liquid water for the ADI v-WCPC. The measured 50% detection diameters (d50) were in the range of 1.3 – 2.4 nm for the tungsten oxide particles depending on the particle charging state and CPC temperature settings, and between 2.5 and 3.3 nm for the organic test aerosol for the 3777 and v-WCPC. The d50s were measured for the B3010 with negatively charged tungsten oxide particles with four different inlet flow rates. The v-WCPC and 3777 were also compared side by side by measuring atmospheric aerosol, exhibiting an excellent agreement.

1 Introduction

The work of Stolzenburg and McMurry (1991) started a new chapter in aerosol research with their prototype laminar flow condensation particle counter (CPC) capable of detecting 3 nm particles via condensation of butanol vapor. The significant improvements in the instrument included minimized diffusion losses in the sampling line and a sheath flow in the condenser to focus the particle beam in the maximum butanol supersaturation in the middle of the condenser (Wilson et al., 1983). This instrument is the predecessor of the ultrafine CPC 3025A and 3776 (TSI Inc., Shoreview, USA), which currently are widely used in various fields of aerosol science to study particle dynamics at particle sizes larger than 3 nm (e.g. Aalto et al., 2001; Weber et al., 1996).

It was not possible to detect particles smaller than 3 nm with the CPC technology until 1997, when Seto et al. (1997) published their design on the particle size magnifier (PSM) used to study heterogeneous nucleation of dibutyl phthalate vapor onto small ions. Their advances were made possible by the development of a new differential mobility analyzer (DMA) combined to an electrospray source, allowing the testing of the CPC with well-characterized monomobile samples. The CPC itself was based on the design of Okuyama et al. (1984), which is a mixing type CPC. It took until 2011 to commercialize the mixing type CPC technology, when Vanhanen et al. (2011) published their version of the diethylene glycol (DEG) based PSM, today sold as the Airmodus A10 PSM (A11 nano condensation nuclei counter when combined to Airmodus A20 butanol CPC).

The first use of DEG as a working fluid was by Iida et al. (2009), who studied sub-3 nm particle detection with various different working fluids theoretically and experimentally. They modified the TSI 3025A to operate with DEG and showed particle activation and growth down to 1 nm. Because the DEG droplets formed are small, a traditional, butanol based CPC is used as a detector. The idea of using the commercial TSI instrument with modifications to operate with DEG has been followed by several other researchers (Jiang et al., 2011a; Jiang et al., 2011b; Kuang et al., 2012a; Kuang et al., 2012b; Wimmer et al., 2013). In 2016 TSI commercialized a DEG instrument based on the work of Iida et al. (2009). This instrument, the TSI 3777 nano enhancer (3777), is one of the three instruments characterized in this study.

Generally, laminar flow ultrafine CPCs use a sheathed condenser, which makes the CPC design more complex compared to non-sheathed CPCs. Yet recent efforts have shown lower detection limits with unsheathed laminar-flow instruments. Particle detection with the butanol-based TSI 3010 has been shown down to 2.5 nm from the factory settings d50 (diameter at which 50% of sampled particles are detected) of 10 nm (Mertes et al., 1995; Russell et al., 1996; Wiedensohler et al., 1997). Kangasluoma et al. (2015a) showed 1 nm particle detection with the commercial unsheathed condenser CPCs TSI 3772 and Airmodus A20 by increasing the temperature difference between the saturator and condenser up to 40 °C. The second CPC characterized in this study is a boosted TSI 3010 (B3010), which is a modification of the commercial TSI3010 developed at the Université Blaise Pascal in which the temperature control of the saturator and condenser is decoupled to allow free selection of the temperatures, and critical orifice is replaced with a flow meter and a miniature rotary vane pump.

The disadvantage of all the previous CPCs is the slight toxicity of the working fluids butanol and DEG. Hering et al. (2005) addressed this issue by developing a water based, laminar technology (Hering and Stolzenburg, 2005), which was commercialized as the TSI WCPC models 3785 (Hering et al., 2005) and 3786 (Ida et al, 2008), and subsequently as the 3783, 3787 and 3788. In the Model 3786, and later in the Model 3788 (Kupc et al., 2013), small particle detection was enabled by introducing similar sheathed condenser as in the butanol based CPCs

The ADI versatile WCPC (v-WCPC), which is the third CPC characterized in this study, advances the laminar-flow water-based CPC through a three stage design that reduces the water vapor concentration and temperature in the growth tube after the peak supersaturation is achieved, and yet allows for continued particle growth (Hering et al., 2016). This three-stage approach facilitates higher temperature differences between the first two stages, and can produce higher peak supersaturation values than the ultrafine TSI 3786 or TSI 3788. The v-WCPC is an unsheathed instrument, operating at an aerosol flow of 0.3 litres per minute (lpm) and at more extreme temperatures than all of the current commercial TSI WCPCs. In contrast to the DEG-based instruments, which require a separate CPC as a detector due to the small size of the DEG droplets, the droplets formed in the growth tube of the v-WCPC are sufficiently large to be detected directly.

The aim of this study is to characterize the performance of the v-WCPC and 3777 with two different types of test particles, to measure effect of charge to the detection efficiency and to compare the instrument responses in atmospheric sampling. The performance of the B3010 was characterized with tungsten oxide particles for different aerosol flow rates.

2 Experimental

2.1 Condensation Particle Counters

A flow diagram of the 3777 is presented in Figure 1. The design is largely similar to the TSI ultrafine 3776. The inlet flow rate is 2.5 lpm, of that 1.5 lpm being transport flow and 1 lpm split as the sheath flow (0.85 lpm) and aerosol flow (0.15 pm). The sheath flow passes through a dessicant drier to remove most water vapor entering the condenser, possibly altering the detection efficiency of a DEG based CPC (Iida et al., 2009; Kangasluoma et al., 2013). Downstream of the drier the sheath flow is

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saturated with DEG before entering the condenser around the aerosol flow, which is guided in the centre line of the condenser. The 3777 does not have its own optics head, as the droplets formed by DEG condensation are too small for direct detection. Instead the detector is a TSI 3772 CPC, which further enlarges and then counts the droplets pre-grown by DEG in the condenser. The factory settings of the 3777 are: saturator 62 °C and condenser 12 °C (low temperature difference (dT) settings). At these settings the 3777 did not detect any ions produced by a radioactive ^{241}Am source. It was also operated at boosted settings so that the supersaturation was at the onset of homogeneous nucleation. With the boosted settings the saturator was 70 °C and condenser 7 °C (high dT settings).

Flow diagram of the ADI v-WCPC is presented in Figure 2. The v-WCPC does not require a separate CPC for droplet detection, nor does it use a sheath flow, making it a relatively simple CPC. The v-WCPC has two flows, a transport flow and an aerosol flow, both of which are controlled by critical orifices. For experiments conducted here the inlet flow rate of the v-WCPC was 2.2 lpm, of which 1.9 lpm is transport flow and 0.3 lpm aerosol flow. The aerosol flow passes upward through a three-stage growth tube consisting of a cool-walled conditioner, followed by a short, warm-walled initiator, and subsequently followed by a cool-walled moderator (Hering et al., 2014). A continuous wick spans all three growth tube sections. Liquid water is injected at a rate of 1 µL/min at the initiator, and excess drains toward the inlet and is removed with the transport flow. Peak supersaturation and particle activation occurs within the initiator, and growth continues in the moderator. The formed droplets are counted by an optics head mounted directly at the outlet of the growth tube. Further detail is presented by Hering et al. (2016). The v-WCPC was tested at two different temperature settings: conditioner at 8 °C and initiator at 90 °C (low dT settings), corresponding to supersaturation low enough to not detect any ions from a radioactive source, and boosted settings with conditioner at 1 °C and initiator at 95 °C (high dT settings), which is close to the extremes attainable without freezing or boiling. In both instances the moderator was operated at 22°C, and the optics head at 40°C.

The B3010 is based on a cheap second hand TSI 3010, from which everything except the saturator block, the condenser and the optical detector are removed. The original electronics have been completely replaced with custom made boards, to handle the higher power consumption, and operate off 28 VDC, the primary power supply in aircrafts. The whole system is controlled by a credit card sized ARM computer, running a tailor-made embedded Linux operating system. It features a touchscreen, a TSI-like serial port protocol, and TTL pulse output. With these modifications the saturator heating and condenser cooling are decoupled. In addition, the critical orifice and external heavy pump are replaced by a laminar flowmeter and a miniature rotary vane pump. The user may set the temperature of the saturator, condenser and optics as well as the flow rate, independently from one another. The B3010 was operated at saturator temperature 55 °C, optics head 56 °C and condenser 11 °C. The B3010 will be described in more details in a dedicated article, presently in preparation. Table 1 summarizes the instrument operation conditions.

2.2 Aerosol generation

Two methods were used to generate the test aerosol: glowing wire generator (GWG) and electrospray source. In the GWG (Peineke et al., 2006), a thin, 0.4 mm in diameter, tungsten wire is heated resistively in a metal chamber. The wire is flushed with 5.0 N_2 flow and it has been shown that negatively charged tungsten oxide clusters are formed into the N_2 flow without additional charging (Kangasluoma et al., 2015b). Positively charged clusters contain some hydrocarbon molecules clustered with tungsten oxide, explaining why usually the measured d50 usually is larger for positively than negatively charged clusters (Kangasluoma et al., 2016b). The d50 for all three CPCs, at two different temperature settings for the 3777 and v-WCPC and at one settings for the B3010, was measured with tungsten oxide particles by size selecting 18 different sizes of particles between 1 and 4.5 nm with the Herrmann type high resolution DMA (Kangasluoma et al., 2016a) (Figure 4). The tubing lengths downstream of the DMA were selected to be equal for the vWCPC, 3777 and electrometer so that the particle penetration through the tubes can be considered equal. For the B3010 the line length was approximately half of the electrometer tubing for the same reason. The d50 of the 3777 was measured at four different sample flow dew points with negatively charged tungsten oxide particles. Water vapor was added to the sample flow with a humidified dilution flow downstream of the DMA. The d50 for the B3010 was measured also at four different aerosol flow rates, 0.5, 1.0, 1.4 and 1.6 lpm, by varying the rotary vane pump speed.

The electrospray source produces charged sample molecule containing droplets by spraying liquid at high voltage out of a capillary needle against a grounded electrode. The charged droplets are close to the Rayleigh limit, and produce charged sample molecules and clusters to the gas flow by series of Coulomb explosions, and ion and solvent evaporation from the droplet. The highly charged droplets can be close to 2 nm in mobility diameter (Ude and Fernández de la Mora, 2005), for which we neutralized the flow exiting the electrospray with a radioactive ^{241}Am source to also be able to sample the clusters larger than 2 nm (Kangasluoma et al., 2016a). The electrosprayed sample in the experiments was tetradodecylammonium bromide (TDDABr) (Ude and Fernández de la Mora, 2005). d50 was measured for the 3777 and v-WCPC with TDDABr with the low dT settings, and for the v-WCPC at the high dT settings. For the 3777 we could not measure the d50 at high dT settings due to the fact that the aerosol-to-sheath flow ratio is very sensitive to the CPC inlet pressure, and TDDABr was produced by drawing the flow out of the DMA, leading to a pressure drop of approximately 5 kPa at the CPC inlets. This pressure drop was enough to alter the aerosol-to-sheath flow ratio in the 3777 and cause homogeneous droplet formation at high dT settings.

To measure the d50 for neutral particles, we followed the approach presented in our previous studies (Kangasluoma et al., 2015b; Kangasluoma et al., 2016b). The sample flow downstream of the DMA passes through a mixing chamber, to which a tube containing a ^{241}Am radioactive is connected. 0.2 lpm of the sample flow is drawn through the tube, and ions from the radioactive source are drifted to the mixing chamber against the counter flow with an electric field. A fraction of the sample particles are neutralized by the opposite polarity ions drifted to the mixing chamber. An ion precipitator is placed downstream of the mixing chamber to allow sampling of only neutral particles with the CPC. The concentration detected with the CPC is normalized against the electrometer. The detection efficiency curve is further normalized with detection efficiency of the largest selected diameters where the role of charge on the detection efficiency is assumed to be negligible. This method yields uncertainties in the resulting d50 due to possibly size dependent neutralization efficiency and chemical composition of the neutralized particles, however, it is being the only method to measure d50 for neutral particles for sub-3 nm particles. Neutral d50 was measured for both instruments with high and low dT by neutralizing both negatively and positively charged particles.

2.3 Ambient sampling setups

The response of the v-WCPC was measured against the TSI electrometer (model 3068B) at different concentrations at sizes 1.4nm, 1.8nm, 2.4nm and 4.4 nm. The concentration at each size was controlled by adding a dilution flow of compressed and filtered air downstream of the DMA. Simultaneous data were collected for the 3777, however the dilution flow was enough to change the aerosol-to-sheath flow ratio of the 3777 due to a small change in the inlet pressure, and therefore the 3777 data of this experiment are not presented. However, assuming that any possible undercounting at high concentration originates from particle coincidence in the optics, the concentration calibration of the 3777 should be practically the same as of the 3772 CPC when the dilution of 0.15/1 is taken into account.

Finally, the 3777 and v-WCPC were placed to sample atmospheric aerosol from Helsinki city area. The instruments were sampling from the same inlet for approximately 18 h to compare the measured concentrations from atmospheric aerosol. The v-WCPC data were dead-time corrected using the dead time correction factor derived from the concentration dependent response for 4.4 nm.

3 Results

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3.1 Detection efficiency

Figure 5 presents the d50 measurements for the B3010, 3777 and v-WCPC at low dT settings for positively and negatively charged tungsten oxide particles. The standard deviation in the detection efficiency data was in most cases < 5%, which is why it is not plotted in the figures. X-axis uncertainty can be taken from the Herrmann DMA resolution of approximately 20, which leads to relative uncertainty of ± 5% based on the selected mobility peak full width at half maximum of 5%. Therefore, uncertainties in the data arise mostly from other sources, such as unequal sampling line penetration or possibly changing particle chemical composition as a function of size. At these settings none of the CPCs detect the ions generated by a bipolar ion source, such as is commonly used for mobility based particle size distribution measurements. We find that the v-WCPC exhibits slightly lower d50 than the 3777, while the d50 of the B3010 is clearly the highest. The d50 of 3.2 – 3.4 nm for the B3010 however shows that the conventional TSI 3010 can be boosted to similar performance as the TSI ultrafine 3776, just with a shallower d50 curve due to larger particle diffusion losses, by decoupling the heating and cooling of the saturator and condenser. Respective d50 values for the B3010, v-WCPC and TSI-3777 are 3.4 nm, 1.7 nm and 1.8 nm for negatively charged tungsten oxide, and 3.2 nm, 1.9 nm and 2.0 nm for positively charged.

At high dT settings the d50 curves are presented in Figure 6. For the 3777 the temperatures were selected as those that are just below the limit of homogeneous nucleation of the DEG working fluid. For the v-WCPC, the temperatures are simply the largest extremes attainable without freezing or boiling the water working fluid. Unlike the DEG instrument, the high dT operation of the v-WCPC is not near the homogeneous nucleation limit, as no evidence of homogeneous nucleation was observed even at reduced inlet pressures. At these higher dT settings, we find somewhat more efficient detection of smaller particles by the 3777 than the v-WCPC. The d50s are lowered to 1.4 nm and 1.3 nm for negatively charged, and to 1.5 nm and 1.4 nm for positively charged for the v-WCPC and 3777, respectively.

Table 2 summarizes the measured d50 for all experiments. The d50 for 3777 and v-WCPC at both settings is lower for negatively charged particles than for positively charged particles. This is observed throughout the past literature (Kangasluoma et al., 2014; Kuang et al., 2012b; Sipilä et al., 2009; Stolzenburg and McMurry, 1991; Winkler et al., 2008), and explained by hydrocarbon contaminants in the positively charged particles (Kangasluoma et al., 2016b). Based on previous literature (Kangasluoma et al., 2014; Kuang et al., 2012b) slightly lower d50 values can be expected for inorganic salt particles than the measured d50s for tungsten oxide particles in this study. TSI states in their instrument brochure a d50 of 1.4 nm for negatively charged NaCl particles at factory settings (low dT in this study), which is well in line with this study. Similarly, the d50 values reported here for the v-WCPC are close to those observed by Hering et al. (2016) who measured d50 of 1.6 nm and 1.9 nm for high dT and low dT operation, respectively, for particles from a heated NiCr wire.

Figure 7 presents the d50 curves for the neutralized tungsten oxide particles. The data is normalized so that the mean of 3 largest diameters is 90% based on the assumption that at those sizes the charge does not affect the detection efficiency anymore. Also is assumed, through the normalization that the neutralization efficiency does not change as a function of the particle size. Further uncertainties arise from the unknown processes that take place during neutralization. Due to these uncertainties, the curves are not as smooth as for the charged particles. However, an estimate for the neutral d50 will be obtained from these experiments, which are 1.6 nm and 1.5 nm for v-WCPC and 3777 at high dT, and 2.0 nm and 1.9 nm at low dT settings, respectively, for neutralized negatively charged tungsten oxide. For positively charged particles the respective values are 2.2 nm and 2.1 nm at high dT settings and 2.4 nm and 2.3 nm at low dT settings (Figure 9). The neutral d50s are greater than for charged d50 values by approximately 0.1-0.5 nm at low dT settings, similar to that obtained in Kangasluoma et al. (2016b) for water-tungsten oxide and DEG-tungsten oxide system.

The d50 curves for positively charged TDDABr for the 3777 and v-WCPC are presented in Figure 9. For both instruments the d50 values are higher than for tungsten oxide particles, but this is most pronounced for the v-WCPC. At the low dT settings d50 values are 3.3 nm and 2.5 nm at for the v-WCPC and 3777 respectively, and 2.8 nm for the v-WCPC at high dT. At the high dT and the reduced inlet pressure for these TDDABr tests, the 3777 produced homogeneously nucleated particles, and hence its high dT d50 value could not be measured. These differences in the d50 imply that the CPCs should be calibrated with the same aerosol composition as with the real experiment is conducted.

3.2 Effect of sample dew point for the 3777

Because water-contamination was observed as a source of error in the original laminar-flow DEG instruments, this question was examined for the 3777. The response of the 3777 for negatively charged tungsten oxide particles as a function of sample flow dew point is presented in Figure 10. The observed variation with dew points ranging from completely dry gas to 20 °C in the d50 is only approximately 0.1 nm. The apparently increased plateau value for the highest dew point can be due to slightly higher inlet pressure, increasing the aerosol flow of the instrument. The variation in the d50 due to changing dew point is less than compared to for example 0.3 nm reported in Kangasluoma et al. (2013) for the Airmodus A09 PSM. This is due to the smaller amount of sample flow water vapor reaching the condenser in the 3777, since 85% of the condenser flow is dried, as compared to 0% of the condenser flow of the PSM of that time. At that time the PSM used internal pumps, today they are replaced by mass flow controllers which are usually fed by dry compressed air, resulting to dried condenser flow fraction from 4% to 34% depending on the instrument operation.

3.3 Effect of flow rate on the B3010

Results from the inlet flow rate experiment for the B3010 is presented in Figure 11. The d50 curve at aerosol flow rates of 0.5, 1, 1.4 and 1.6 lpm are rather similar within the experimental uncertainties, while at flow rate of 0.5 the detection efficiency clearly deviates to lower values at particle diameters larger than 3 nm. This can be possibly due to larger final droplet diameters and subsequent gravitational losses at the low flow rate. Similar increase in the detection efficiency with higher flow rate as in Kangasluoma et al. (2015a) was not observed, which can be due to the differences in the saturators between the 3010 and 3772: 3010 has a single hole reservoir type saturator while 3772 has 8 hole multitube saturator which possibly saturates the sample flow better than the one hole saturator at higher flow rates.

3.4 Concentration calibration

As with all CPCs, the peak supersaturation, and hence the lowest detectable particle size is can be affected by the presence of other particles in the flow, due to a combination of condensational heat release and vapor depletion. These effects for the original WCPCs were explored by Lewis and Hering (2013), and is evaluated here for the v-WCPC. Figure 12 shows the concentration dependent response at four particle sizes for the v-WCPC. The maximum concentration at each size was determined by the maximum concentration we were able to pass through the DMA. The data are corrected for dead time, as described by Hering et al. (2005), and as is standard for most of the commercial CPCs. This approach uses the instrument dead time multiplied by a dead time correction factor, which accounts for the increase in effective dead time due to overlapping tails in pulses below the threshold. For this data set the dead time correction factor was set to 1.23 to yield a linear response to concentration at 4.4 nm. Then this same dead time correction factor was applied to measurements at other sizes. The curves of the three smallest particle sizes have a negative slope due to the reduction in supersaturation at high concentrations caused by condensational heating (Lewis and Hering, 2013).

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However, the effect is relatively small, with the detection at 1.8 nm dropping from 36% at a concentration of 3000cm^{-3} to 33% at a concentration of 90000cm^{-3}.

3.5 Atmospheric sampling

A fraction of the data measured from atmospheric aerosol is presented in Figure 13. The measurement location is above a bus stop, which several busses pass daily through. The bus stop times are marked to the figure. The background aerosol concentration during that morning was around 3 000 – 10 000 cm^{-3}. Clear spikes up to 200 000 cm^{-3} in the measured concentrations are observed throughout the morning, of which timing match quite well the scheduled bus departure times. From the data of Figure 13, a correlation plot between the v-WCPC and 3777 is presented in Figure 14 for concentrations below 50 000 cm^{-3}. With R^2 of 0.99 the two CPCs show remarkably good agreement with slope of 1.02 and offset of 340 up to concentrations of 50 000 cm^{-3}.

4 Conclusions

Three new sub 3 nm CPCs, boosted 3010 type CPC, ADI versatile water CPC and the TSI 3777 nano enhancer were characterized for the d50 diameter. The boosted 3010 type CPC was shown to be able to detect tungsten oxide particles smaller than 3 nm. The vWCPC and 3777 were characterized with similar test aerosols with two different settings: low dT settings set so that the CPCs did not detect any ions from a radioactive charger, and high dT settings set either so that the supersaturation was at the onset of homogeneous droplet formation (3777) or set to the largest value that avoids freezing or boiling (v-WCPC). The d50 diameters for tungsten oxide were found to range from 1.7 nm to 2.4 nm at low dT and from 1.4 nm to 2.2 nm at high dT for the v-WCPC. For the 3777 the d50 ranged from 1.8 nm to 2.3 nm at low dT and from 1.3 nm to 2.1 nm at high dT. Both CPCs were observed to detect charged tungsten oxide particles better than neutral ones. The organic salt particles (TDDABr) were detected less efficiently, with low dT d50 diameters of 3.3 nm for the v-WCPC, and 2.5 nm for the TSI-3777. When measuring the same atmospheric aerosol the two CPCs showed a very good agreement with regression slope of 1.02 and R^2 of 0.99.

From the results we can make the following conclusions: The TSI 3010 hardware can be tuned to accomplish 3 nm particle detection by increasing the dT but not by increasing the inlet flow rate, which is in line with Buzorius (2001). This is possibly due to not perfect flow saturation in the reservoir type saturator as opposed to the multihole saturator of TSI 3772 and planar type saturator of Airmodus A20 (Kangasluoma et al., 2015a). Due to the variations in the d50 with composition for the vWCPC and 3777, their use as a detector downstream of a DMA is suggested only if the particle composition is known and CPC calibration is made accordingly with the same particle composition, or with sizes above the highest d50 (approximately 2.5 – 3 nm) if the particle composition is completely unknown. The effect of particle charge on the d50 was show to be up to approximately 0.5 nm, which has implications on to system characterizations where the fraction of charged particles can be expected to be high (Wang et al., 2017), or CPC calibration is conducted with charged particles and sampled particles are neutral, and high precision d50 is required.

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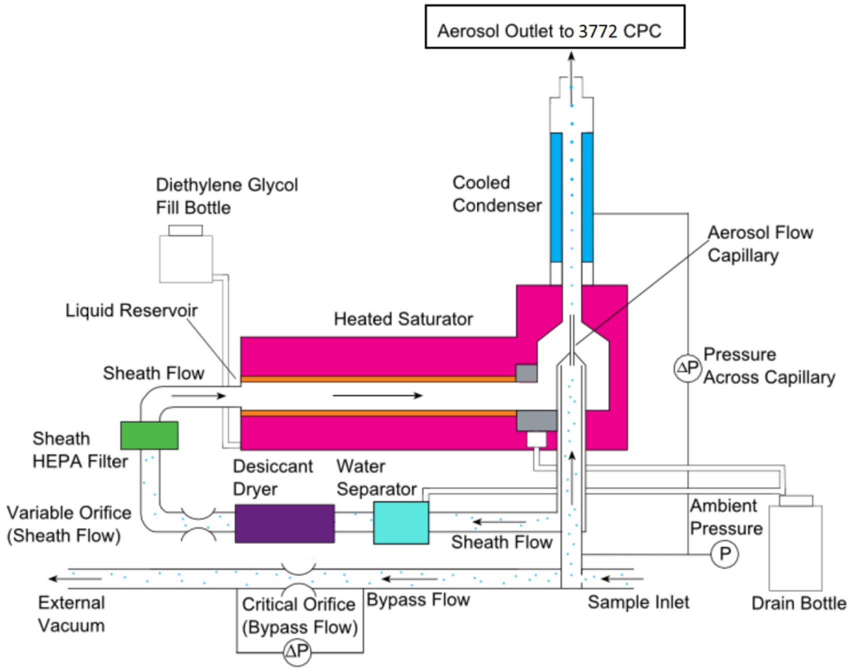

Figure 1. TSI 3777 nano enhancer (courtesy of TSI Inc.)

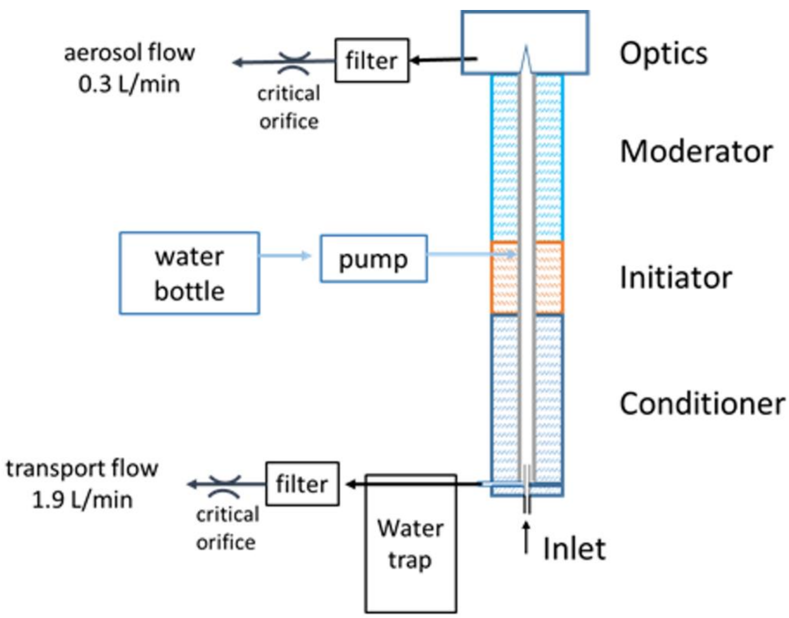

Figure 2. ADI v-WCPC

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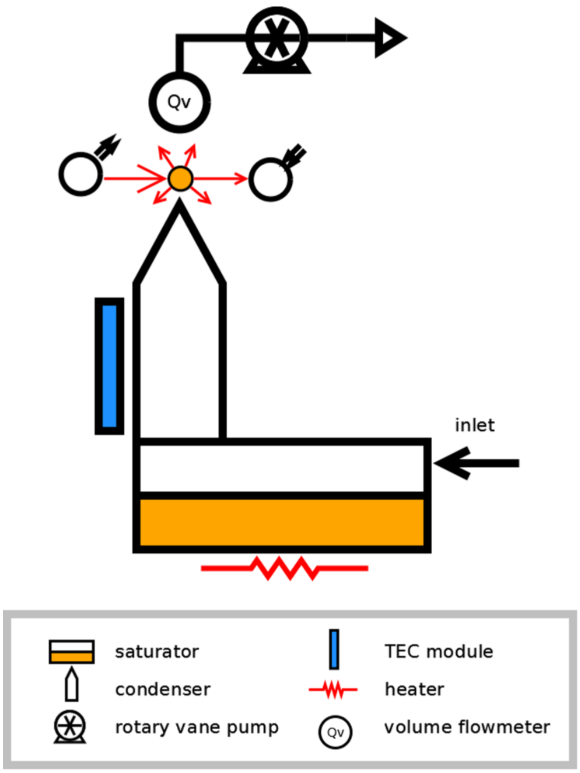

Figure 3. B3010.

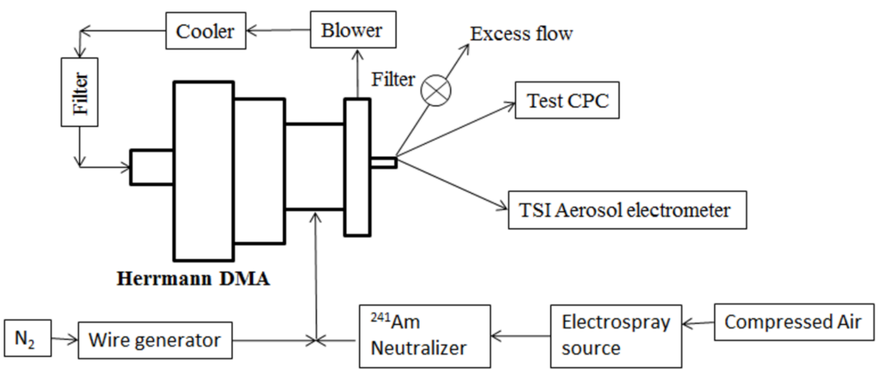

Figure 4. Experimental setup to measure d50 for charged particles

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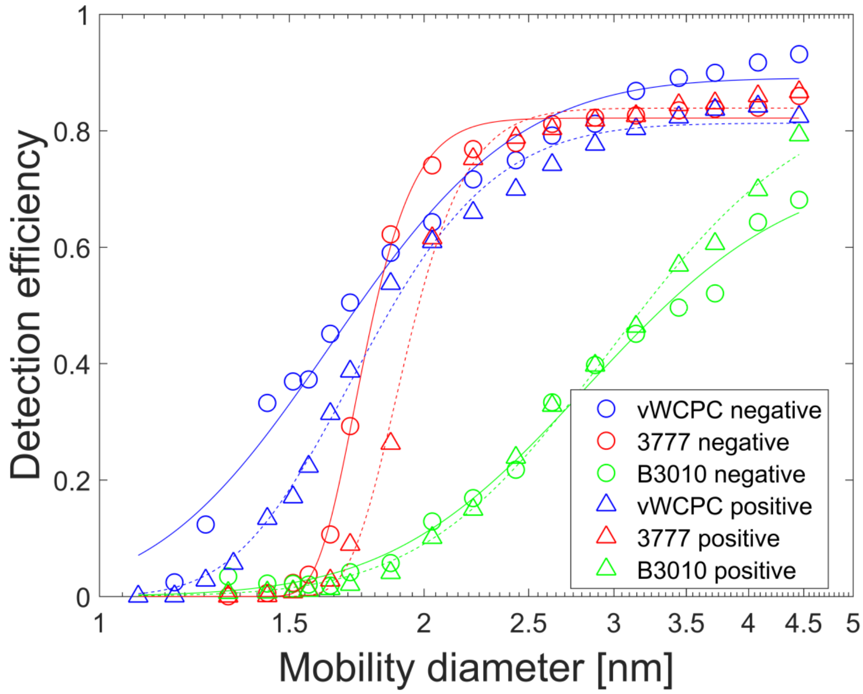

Figure 5. Detection efficiency of the CPCs as a function of size for negatively and positively charged tungsten oxide particles at low dT settings.

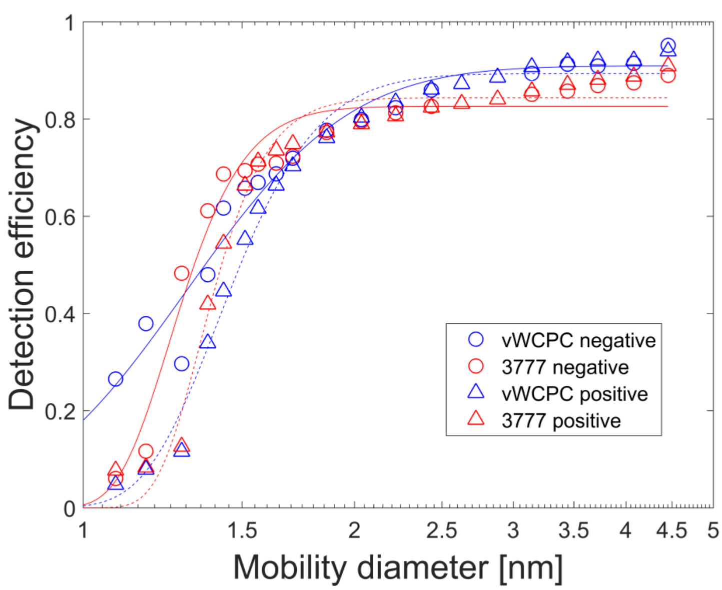

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Figure 6. Detection efficiency of the CPCs as a function of size for positively and negatively charged tungsten oxide particles at high dT settings.

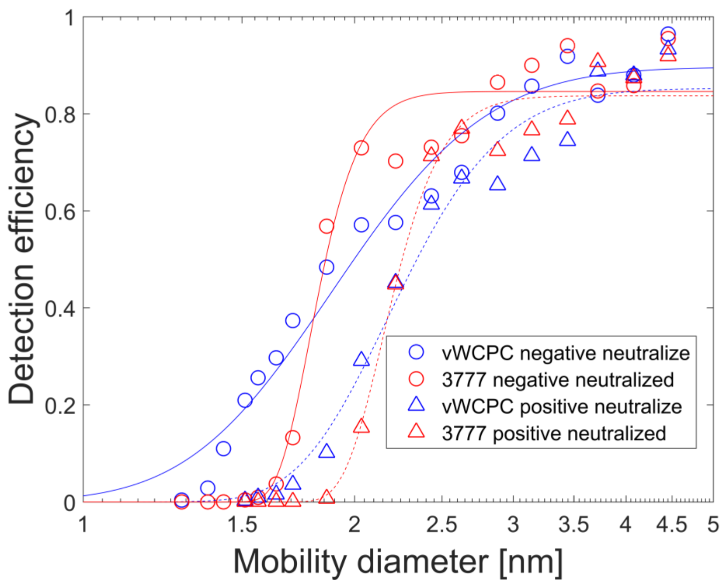

Figure 7. Detection efficiency of the CPCs as a function of size for negatively and positively charged tungsten oxide particles that are neutralized at low dT settings.

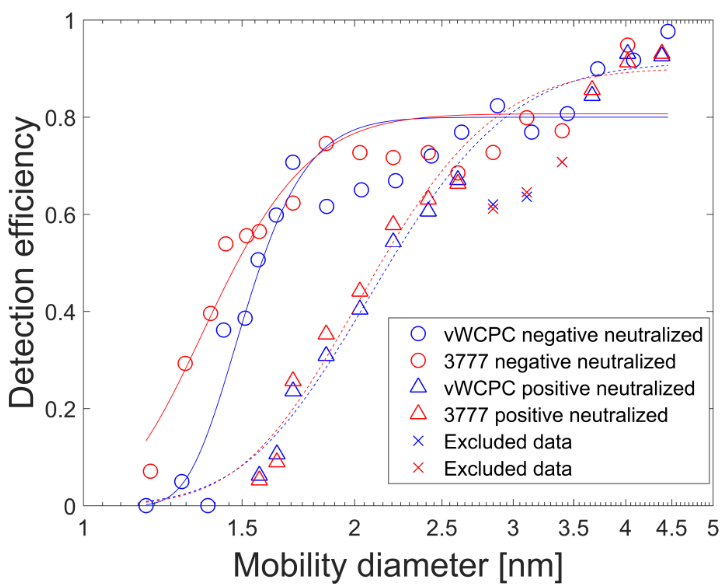

Figure 8. Detection efficiency of the CPCs as a function of size for negatively and positively charged tungsten oxide particles that are neutralized at high dT settings.

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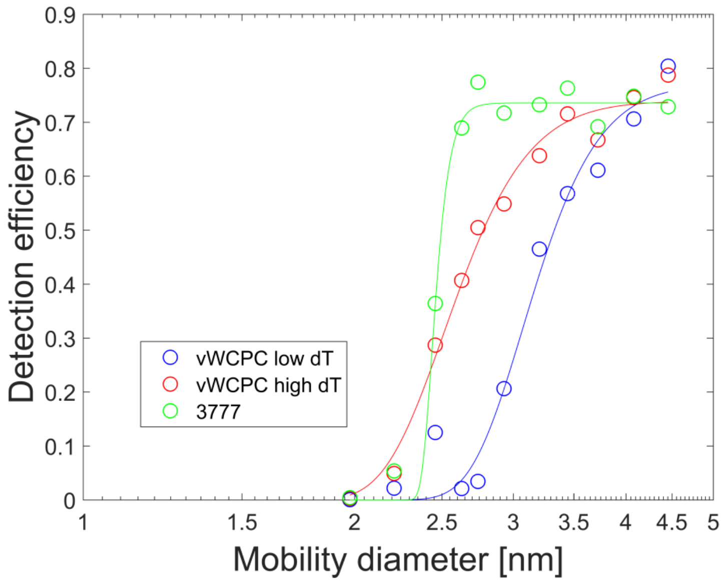

Figure 9. Detection efficiency of the CPCs as a function of size for positively charged TDDABr particles at low and high dT settings for v-WCPC and at low dT settings for the 3777.

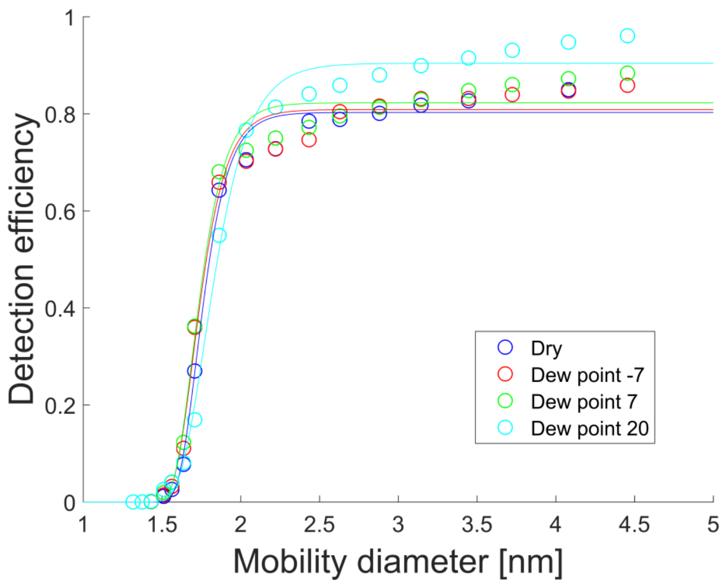

Figure 10. Detection efficiency of the 3777 as a function of the diameter and sample flow relative humidity.

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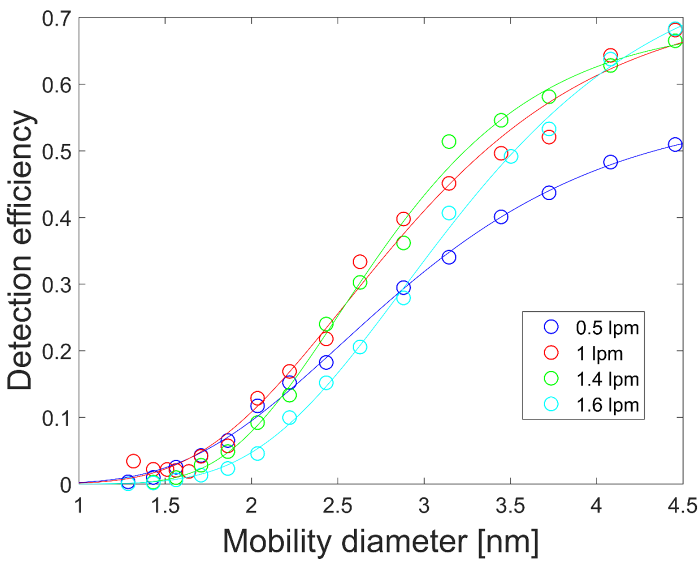

Figure 11. Detection efficiency of the B3010 as a function of the inlet flow rate.

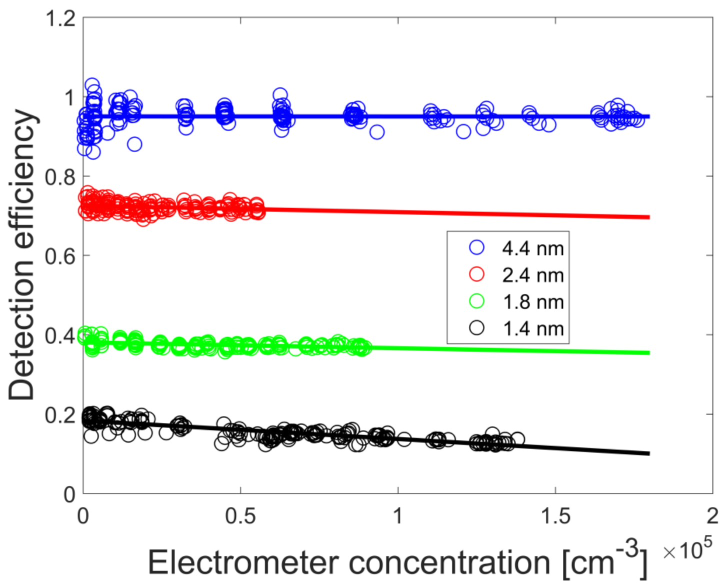

Figure 12. Ratio of the v-WCPC to the electrometer as function of the particle concentration.

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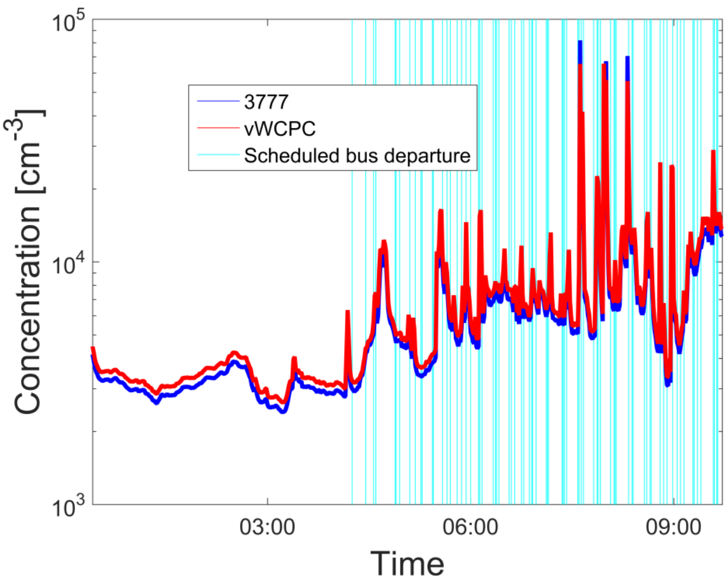

528
529 Figure 13. Concentration measured by the 3777 and v-WCPC from urban atmospheric air.
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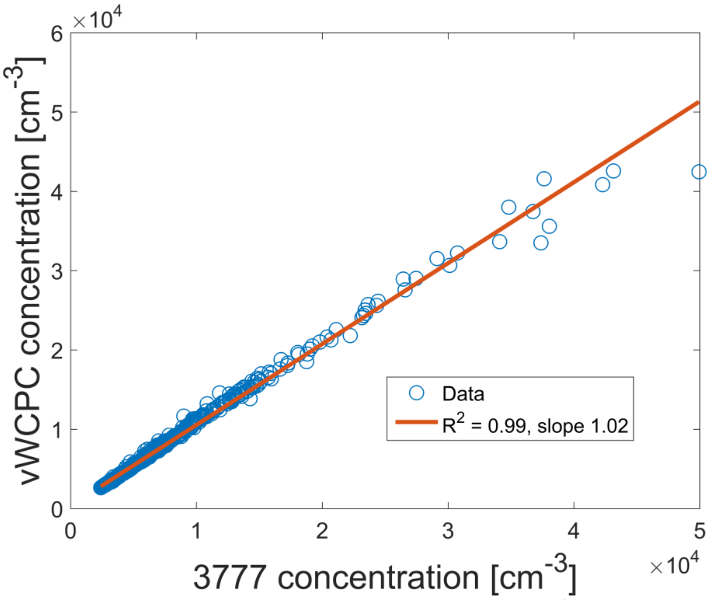

531
532 Figure 14. Correlation of the concentrations below 50 000 cm^{-3} measured by the CPCs for the same
533 data as in Figure 13.
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Table 1. Instrument operation conditions

Instrument	Qinlet [lpm]	Qaerosol [lpm]	Settings	Ts [oC]	Tc [oC]	Tm [oC]	To [oC]
B3010	1	1	Low dT	55	10		56
vWCPC	2.2	0.3	Low dT	8	90	22	40
vWCPC	2.2	0.3	High dT	1	95	22	40
3777	2.5	0.15	Low dT	62	12		
3777	2.5	0.15	High dT	70	7		

Table 2. Indicated Cutpoints

Conditions	Aerosol	Charging state	ADI v-WCPC	TSI-3777	B3010
High dT	WOx	negative	1.4	1.3	NA
High dT	WOx	positive	1.5	1.4	NA
High dT	WOx	neutral from -	1.6	1.5	NA
High dT	WOx	neutral from +	2.2	2.1	NA
Low dT	WOx	negative	1.7	1.8	3.4
Low dT	WOx	positive	1.9	2	3.2
Low dT	WOx	neutral from -	2	1.9	NA
Low dT	WOx	neutral from +	2.4	2.3	NA
High dT	TDDAB	positive	2.8	NA	NA
Low dT	TDDAB	positive	3.3	2.5	NA