Effect of scan time on SMPS particle size measurements

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ABSTRACT: This work investigated the effect of scan time of SMPS (Scanning Mobility Particle Sizer) on the stability and shift of ultra-fine and nano-particles measurement. The particles produced from distilled water and salt water (0.020%wt) by an aerosol generator were measured for number concentrations and size distributions using a SMPS. The scanning time of the SMPS was set at 30s, 60s, 120s, 180s and 240s. The filtered compressed air was used to blow through the generator to produce particles. The effect of scanning time on particle numbers and size distributions was compared for each condition. A unimodal size distribution of the particles was found in all the examined conditions. The results showed that a shift of particle size distribution towards smaller particles and lower particle number concentrations with shorter scanning times such as 30s and 60s occurred; indicating that the scanning time affects the particle number and size distribution measurements. The SMPS scanning time should choose to be more than 100s to get reasonably reliable results.

Key words: particle size distribution; particle number; SMPS;

1. INTRODUCTION

Particulate matter (PM) is a generic term used to describe a complex group of air pollutants that vary in size and composition, depending upon the location and time of its source. The PM mixtures of fine airborne solid particles and liquid droplets (aerosols) include components of nitrates, sulphates, elemental carbon, organic carbon compounds, acid aerosols, trace metals, and geological material etc. There are many sources that produce particulates including industrial processes, power generation and transportation activities. Particulate matter emissions from combustion sources burning fossil fuels have raised particular interests in the recent years from environmental regulatory agencies due to health effects(Harrison, Shi et al. 2000). The particulate matter is ranging from millimetre-sized residues and soot aggregates to ultrafine nuclei mode particles with only a few nanometres in diameters. Commonly, the large particles are removed or collected by cleaning devices. However, the smaller particles from combustion exhaust gases could be transported over hundreds miles causing serious air pollution problems. Currently PM10 and PM2.5 are regulated by various legislations for engine exhaust, air quality and industrial process et al(Lighty, Veranth et al. 2000) because sub-micrometer particles have a significant risk for human health and environmental quality(Lighty, Veranth et al. 2000).

There are several methods of measuring particle numbers and their size distributions including Scanning Mobility Particle Sizer (SMPS), Electrical Low Pressure Impactor (ELPI) and Differential Mobility Analysis (DMS) etc. Each of these methods has its features based on its measurements technique. It is believed that the time resolution; accuracy and size resolution are key parameters in the measurement of particle size distributions(Tan, Hu et al. 2009). SMPS as

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one of the commonly used methods (Harrison, Shi et al. 2000) has a very good particle size resolution and has been used in various participle measurements (Shi, Mark et al. 2000) . However, the full range size measurements of SMPS have been constrained to steady state process due to its operational principle, which needs at least 20~30 seconds to complete a full range scan. In practice, longer scan durations are commonly used to ensure the reliability of the results (Allouis, Beretta et al.), although the shorter scan duration can be used. There are few studies investigated the effect of SMPS scan time on the particle size distributions measurement. Shi et al (1999) reported measurements of particle size distributions and concentration at a busy roadside in Birmingham, UK using SMPS and ELPI at different sites and time (Shi, Khan et al. 1999). Their results showed that despite the ELPI and SMPS operate on different working principles; a good agreement was found between the instruments at each of the SMPS scan time. Also, they studied the effect of SMPS scan time on size distribution measurements with the scan time of 30, 60, 10 and 200s (Shi, Khan et al. 1999) and found there was a significant shift of peak particle size towards larger particles and higher particle numbers observed when the scan time was short such as 30s and 60s, compared to the longer scan time. The difference in size distributions and number concentrations for different scan times was getting smaller as the scan time increased. They suggested that the main reason behind this shifting is due to the stability of the particles and the longer scan time encompassed the temporal changes in the size distribution. Asbach et al (2009) compared the particle measurements for diesel soot and sodium chloride using four mobility particle sizers with different time resolution: TSI Fast Mobility Particle Sizer (FMPS), Grimm Sequential Mobility Particle Sizer plus Counter (SMPS+C) and two TSI Scanning Mobility Particle Sizers (SMPSs) (Asbach, Kaminski et al. 2009). The FMPS measured the particles with a time resolution of 1s, TSI SMPSs were operated with a long column DMA and time resolution of 300s (240s scan time, 20s retrace and 40s wait) and the total time for Grimm SMPS was 230s when operated with a short DMA and 406s with a long DMA. They found that there was a good agreement between all instruments except FMPS. Grimm SMPS reported higher concentration and broader distribution than that of the TSI SMPSs (Asbach, Kaminski et al. 2009). Tokonami and Knutson (2000) studied the effect of scan time on particle size distribution measurement using SMPS at the scan time of 30, 60 and 300s and concluded that the results from shorter scan times appeared to have greater fluctuations compared to that from the longer scan times. The longer scan time produced lower particle concentrations and higher repeatability by comparison with shorter scan time measurements (Tokonami and Knutson 2000).

This paper investigates the effect of SMPS scan time on the measurements of particle number concentrations and size distributions and quantifies the impact and thus tries to provide an approach for the correction of the short scan time measurements results.

2. EXPERIMENTAL METHODS

2.1 SMPS

A SMPS system with a Nano-Differential Mobility Analyzer (NDMA) was used to determine the number concentration and size distribution of aerosols in the size range from 5 nm to 160 nm. The SMPS is based on the principal of the mobility of a charged particle in an electric field (particle charger). The sample is sucked into the system and passed through an inertial impactor to remove the larger particles and then enter the NDMA to differentiate particles according to their electrical mobility, with only particles of a narrow range of mobility exiting through and counted with a Model 3025 Condensation Particle Counter (CPC). The entire system is automated. Data analysis is performed using a computer system with customized software(TSI 2003).

2.2 Aerosol generator

The Grimm aerosol generator 7-230 is used for producing aerosols in this work. It is able to produce particles with highly constant particle size distributions and particle concentrations with high reproducibility. It is a small size, rugged, reliable and very compact instrument, and consists of a compressed air inlet in the front, a manometer and pressure reducer, a stainless steel atomizer connected to compressed air, a protection valve and the aerosol outlet. The maximum allowable inlet pressure for the compressed air supply is 8bar. The atomizer has a two stream nozzles based on the injection principle and is combined with a baffle plate placed close to the spray outlet. This section removes coarse spray droplets and pass particle with size below 1μm(Technik 2003).

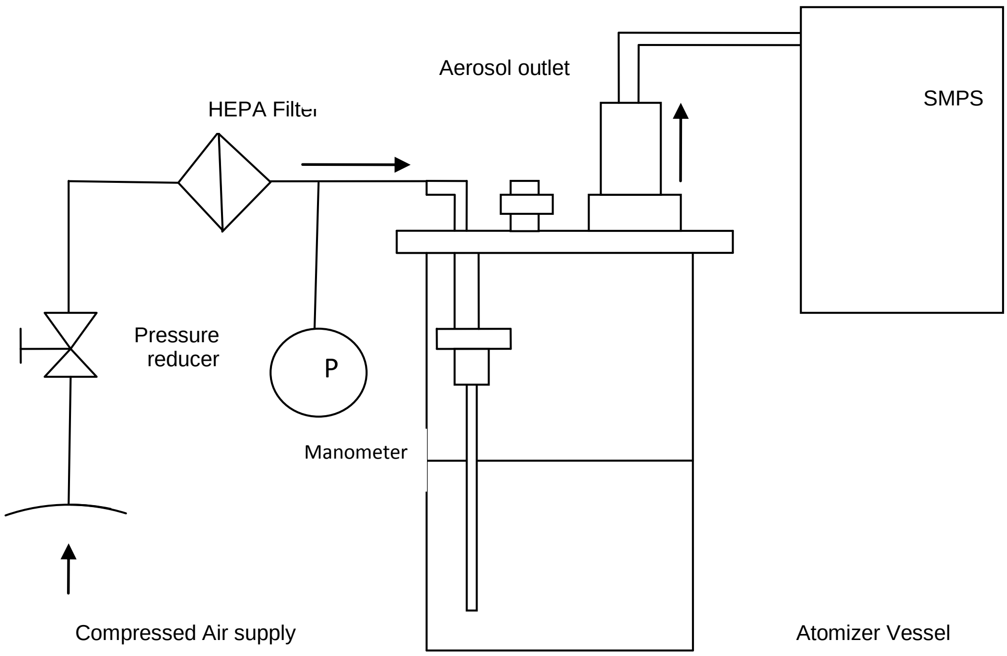

Figure 1: schematic view of experimental setup

2.3 Experimental procedures

The compressed air was filtered using a standard HEPA filter and connected the aerosol generator. The distilled water (DW) and 200ppm (0.02%) salt water (SW) solution were added to the atomizer vessel in turn. The pressure of the compressed air was controlled at 4 and 5 bars respectively to produce the different concentrations of particles suitable for the SMPS measurement range. Five different scan times (30s, 60s, 120s, 180s and 240s) for the SMPS were chosen for the measurements of particle number distributions and size distributions at each particle concentration. All the measurements were taken after the generator reached steady state operations, usually after 10 minutes of start. Four scans were taken at each scan time and concentration. The repeatability between scans was examined and the average result of the four measurements at each scan time and particle concentration was used for the comparisons between different conditions. Figure 1 shows the schematic view of the set up.

3. RESULTS AND DSCUSSION

3. 1 Effect of scan time on particle size distribution

The particle size distributions with different scan times were measured and presented in Figs.2 and 3 for distilled water derived particles and Figs. 4 and 5 for salt solution derived particles. The results show that at all different scan times and both compressed air pressures, the particle size distributions displayed unimodal lognormal distributions. The size of particles generated from DW is in the range of 10nm to 100nm at both pressures. The peak number concentrations at the air pressure of 4 and 6 bars are about $4x10^6$ and $6x10^6$ $1/cm^3$ respectively. The particles at all scan times have nuclei mode with peak concentrations at the particle size between 30nm and 40nm in diameter. The particle size distributions with longer scan times (120, 180&240s) have a very similar behavior with the same peak concentrations and the same shape of the curves at both air pressures. However, for the results of 30 and 60s scan times, it is clearly shown that a shift of particle size distribution occurred. The mode size at which the peak concentrations appeared moved towards larger particles

and the peak particle concentrations decreased.

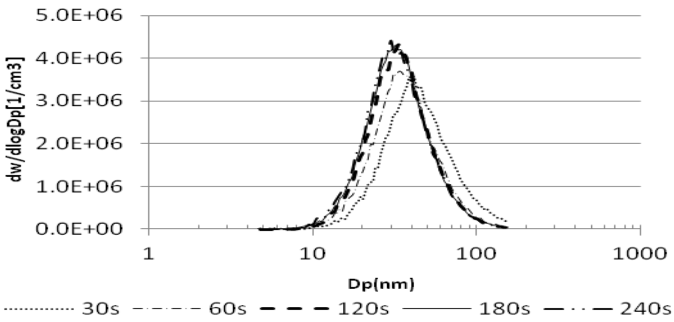

Figure 2: Particle size distribution of distilled water with different scan time at 4bar

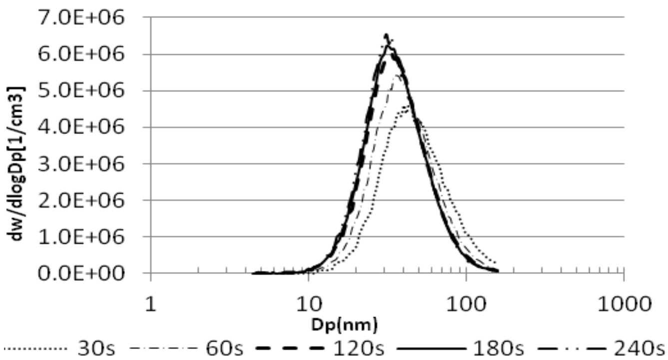

Figure 3: Particle size distribution of distilled water with different scan time at 5bar

The size of particles generated from SW is overall greater compared to particles derived from DW and in the range of ~15nm to 160+nm at both pressures as shown in Figs. 4 and 5. The peak number concentrations at the air pressure of 4 and 6 bars are about $3x10^7$ and $4.5x10^7$ $1/cm^3$ respectively. Similar to the results in Figs. 2 and 3, the particle size distributions with longer scan times (120, 180&240s) are close to one another with the same peak concentrations and the same shape of the curves at both air pressures. Again, a clear shift in particle size distributions for the 30 and 60s scan times occurred. i.e. the particle size at which peak concentrations appeared moved towards larger particles and the peak particle concentrations decreased.

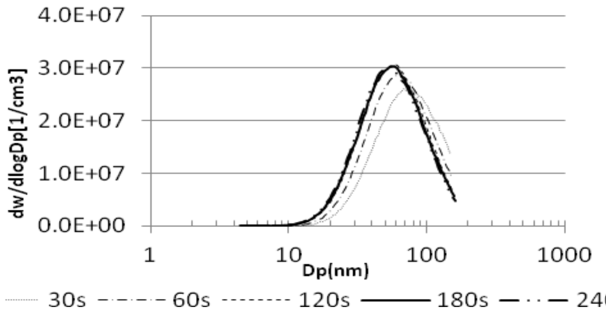

Figure 4: Particle size distribution of 200ppm salt with different scan time at 4bar.

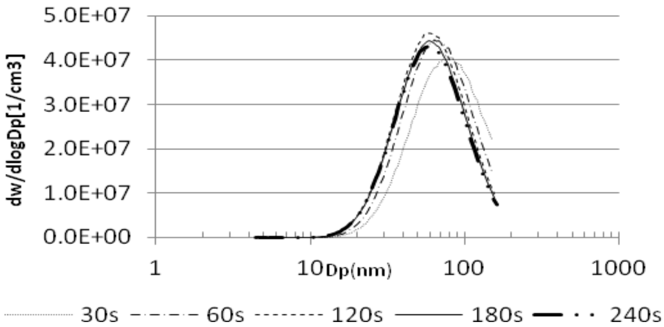

Figure 5: Particle size distribution of 200ppm salt with different scan time at 5bar

3.2 Effect of scan time on total particle concentration, mode size, median and mean

The total particle concentrations for the DW and SW derived particles were plotted as a function of scan time as shown in Fig.6. These total concentrations were then normalised to that at 240s scan time and plotted as a function of scan time as shown in Fig.7. The effect of scan time on the total concentration of the particles was evaluated. A reduction of ~20% for 30s scan time and ~15% for 60s scan time was observed.

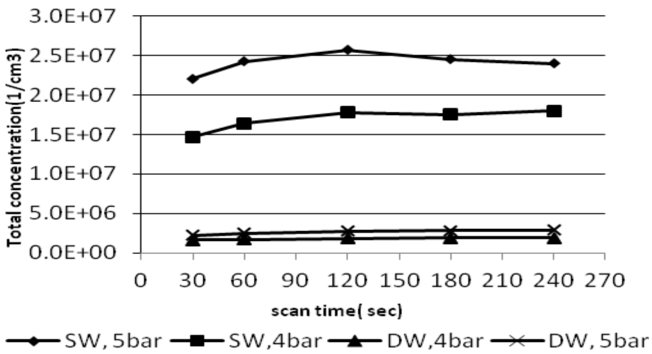

Figure 6: Particle total concentration of DW and SW with different scan time at 4&5bar

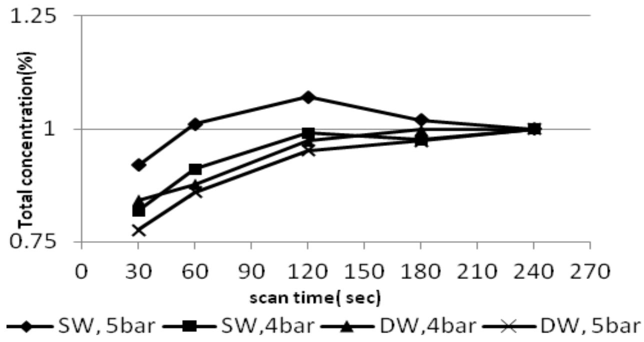

Figure 7: Normalised Particle total concentration of DW and SW to 240s at 4&5ba**r.**

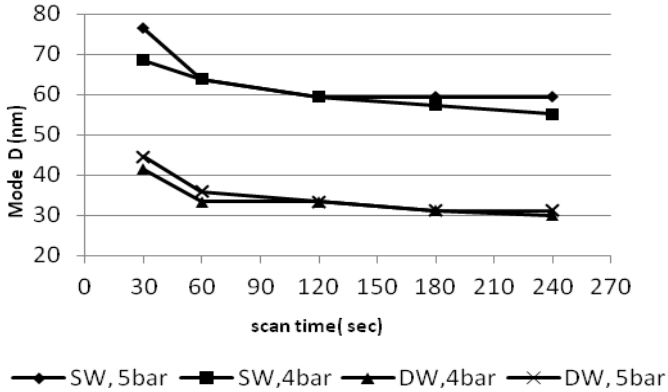

Figure 8: Particle mode size diameter of DW and SW with different scan time at 4&5bar

Fig.8 presents the mode size as a function of scan time. It shows that the most significant influence happened at 30s scan time, where the mode size of particles increased remarkably. As the scan time was getting longer, the mode size of particles was stabilised. This suggests that SMPS scan time should be more than 100s to give a more reliable measurements, which is in good agreements with the study of Tokonami and Knutson(Tokonami and Knutson 2000).

Figs. 9 and 10 show the median and mean of the particles respectively in nano-meters for both DW and SW at 4 and 5 bar. Similar to the results of total particle concentrations and mode size, the most significant deviations occurred at 30s scan time and this was decreased to a stable level after scan time being longer than 100s.

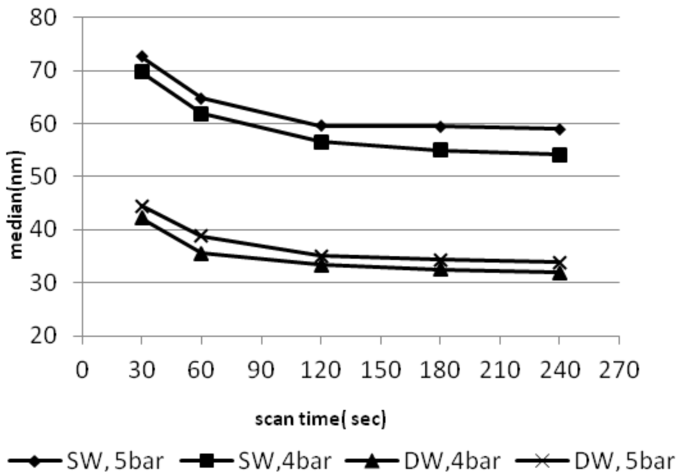

Figure 9: Particle median diameter of DW and SW with different scan time at 4&5bar

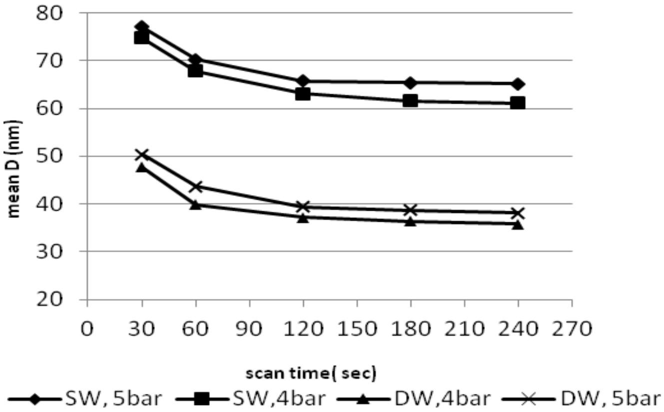

Figure 10: Particle mean size diameter of DW and SW with different scan time at 4&5bar

3.3 Relative deviations analysis as a function of scan time

The results above showed that the measurements were consistant and stable as long as the scan time was long enough (>100s). The results at scan time of 240s could therefore be regarded as a baseline and the relative changes and errors of measurements at other scan times could be determined. The particle size distributions as a function of scan time for DW and SW at 4 & 5bar were normalised to that of 240s as shown in Figs. 11 to 14. The deviations of short scan time results from the baseline show a seesaw shape, i.e. higher than the baseline on the lefthand side of the pivot and lower than the baseline on the righthand side of the pivot. The particles smaller than pivot were positively deviated and ones larger than pivot points were negatively deviated from the baseline. There was no deviation at pivot points. The pivot point was 40-50 nm for DW particles and 70-80 nm for SW particles, which was in effect coincident with mode size. This indicates that the particle size distribution measurements using shorter scan times are overestimated for the particles smaller than mode size and underestimated for the particles larger than mode size. The results in Figs. 11 to 14 show that the measurements for particles less than 10 nm had a huge uncertainty. The particle size distrbutions at 120s and 180s were close to the baseline with an error less than 10% in a size range of 10~140 nm. The senario was different at shoter scan times espacailly at 30s. The relative errors for 30s and 60s scan time results could reach up to ~300% and ~50% respectively, compared to the baseline. The errors were increasing as the scan time reduced. The errors for the particles smaller than mode size were less than that for the particles greater than mode size. These results reflected a relative change from a baseline and could be used to estimate errors from short scan time results and rectify the short scan time measurements,

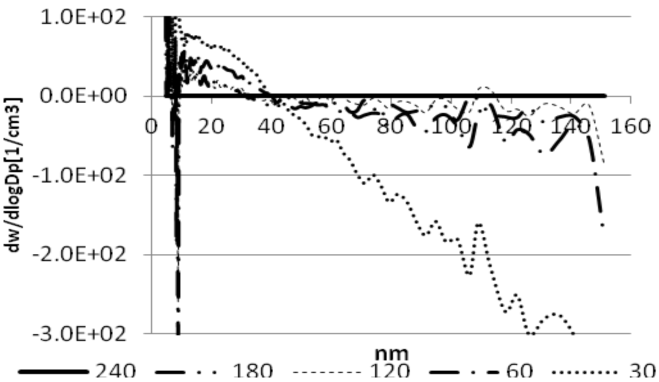

Figure 11: Normalized Particle number as a function of particle size for DW at 4bar

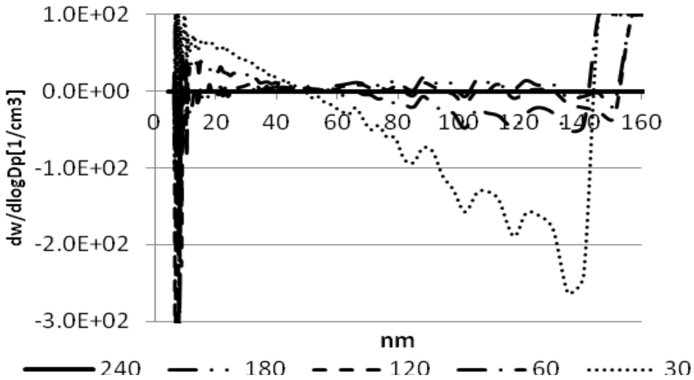

Figure 12: Normalized Particle number as a function of particle size for DW at 5bar DW

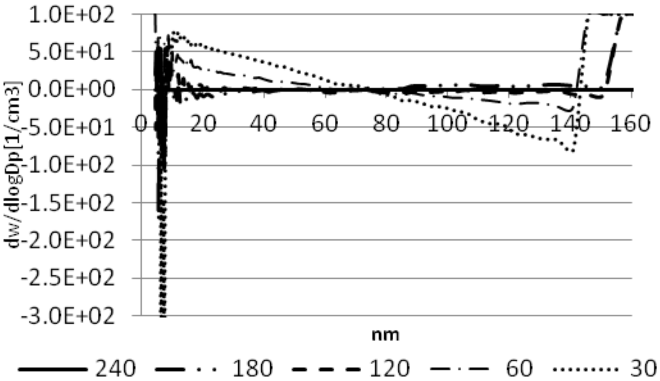

Figure 13: Normalized Particle number as a function of particle size for SW at 4bar

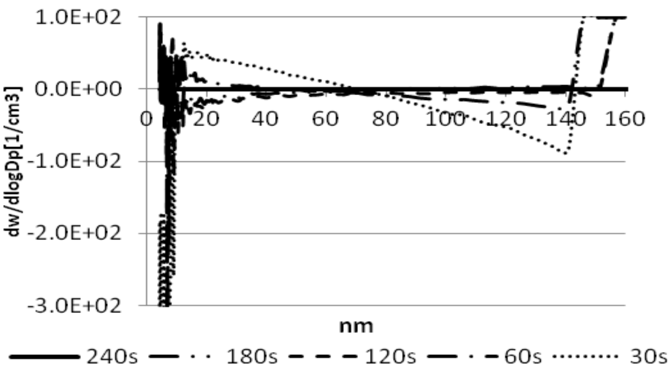

Figure 14: Normalized Particle number as a function of particle size for SW at 5bar

As described earlier, all particle size distributions in Figs 2 to 5 show an approximately normal distribution mode. Thus the standard deviation for each scan time was computed to represent the width of the distributions. Table 1 summarises the standard deviation (SD), mean diameter, median and total particle concentration (cm^{-3}) for all scan times at different particle concentrations. The results show the distribution was the widest with 30 s scan time and getting narrow with 60 s scan and became the same or very close for 120, 180 and 240 s scans. The particle mean and median diameter became smaller as the scan time increased. The measured mean diameter was about 24% and 16% larger for 30s scan time than that of

240s scan time results for DW and SW respectively. The particle concentrations increased as the scan time increased.

3.4 Repeatability and stability of the measurements

In order to reduce experimental uncertainties, all measurements at each scan time setting and particle concentration were repeated at least four times and the average results of the four scans were used for comparisons. The standard deviations of individual scans against the average value were computed for each set of data. Then the ratio of the average standard deviation versus the mean was calculated as percentage and plotted against particle size as shown in Figs. 15 to 18 to represent relative deviations within each set of measurement. A large relative deviation was observed when particles were smaller than 20 nm for all the measurements. For particle derived from the DW, the relative deviations for particles with the size between 25 and 100nm were less than 10% and up to 20% for big particles with the size more than 100nm. For SW derived particles, the relative deviations were less that 5% when the particle size was bigger than 30 nm, which could be decreased to less than 2% as the particle concentrations increased as shown in Fig.18. Overall, the measurements showed a good repeatability. No difference in the repeatability of measurements was observed between short and long scan time.

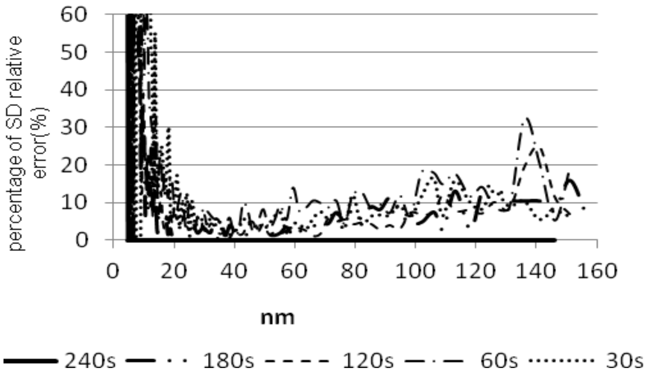

Figure 15: Standard deviation (SD) mean relative error of each scan at 4bar, DW

Table 1: Difference of SMPS response with different scan time of DW&SW at 4&5bar

	Scan time	SD	Mean Diameter (nm)	Median (nm)	Total Concentration (cm^{-3})
DW,4bar	30	1.59	47.7	42.14	1.60E6
	60	1.57	39.84	35.5	1.66E6
	120	1.55	37.25	33.3	1.84E6
	180	1.55	36.39	32.5	1.89E6
	240	1.56	35.8	31.8	1.9E6
DW,5bar	30	1.59	50.4	44.4	2.2E6
	60	1.56	43.6	38.7	2.47E6
	120	1.56	39.4	35.03	2.74E6
	180	1.5	38.72	34.37	2.8E6
	240	1.5	38.13	33.8	2.88E6
	30	1.59	74.7	69.7	1.47E7
	60	1.57	67.7	61.8	1.63E7

SW,4bar	120	1.55	63.07	56.5	1.78E7
	180	1.55	61.51	54.9	1.75E7
	240	1.56	61.01	54.13	1.8E7
SW,5bar	30	1.59	77.07	72.6	2.21E7
	60	1.56	70.2	64.7	2.42E7
	120	1.56	65.7	59.6	2.57E7
	180	1.55	65.4	59.4	2.45E7
	240	1.55	65.2	58.9	2.4E7

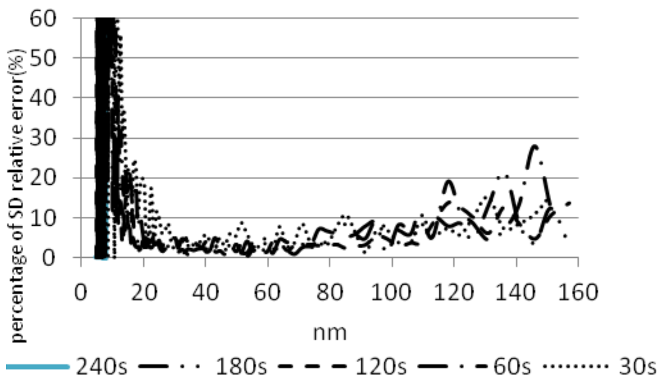

Figure 16: Standard deviation (SD) mean relative error of each scan at 5bar, DW

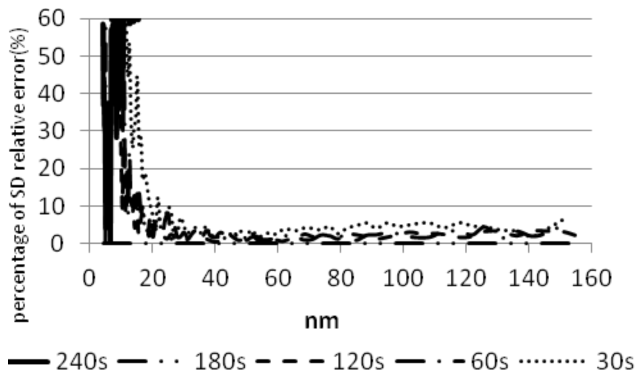

Figure 17: Standard deviation (SD) mean relative error of each scan at 4bar, SW

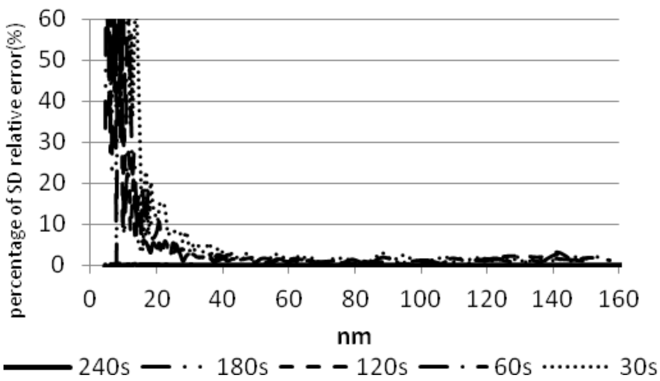

Figure 18: Standard deviation (SD) mean relative error of each scan at 5bar, SW

4. CONCLUSION

The effect of SMPS scan time on particle number concentrations and size distributions was investigated by measuring particles generated from distilled water and 200ppm salt solutions via an aerosol generator. The particles produced show a unimodal distribution although the salt solution produced wider size distributions and larger particle sizes than the distilled water. The size range of particles measured was 5 to 160 nm. The main conclusions are as follows:

1) The results from the shorter scan time such as 30s and 60s showed a shifted size distribution with peak concentrations moving towards larger sizes and reduced peak concentrations, compared to the results from the scan time of 120s and above.

2) It is observed that the size distributions and number concentrations were getting very close to one another for scan time 120s, 180s and 240s. This suggests that a minimum scan time of 100s is preferred to get more reliable results.

3) A significant deviation in the total concentrations of particles was observed when the scan time was at 30s and 60s, compared to that using longer scan times. The reduced scan time increased the total particle number concentrations.

4) The median, mean and mode size of particles was increased up to (20%) with shorter scan times (30 and 60 s), compared to longer scan times. The particle mean size for 30s and 60s scan time was about 24% and 16% larger respectively, compared to the longer scan time results

5) The relative deviation analysis showed that the particles numbers were positively deviated for particles smaller than mode size and negatively deviated for particles larger than mode size from the baseline (240s results). There was no deviation at the mode point. The relative deviations could reach up to ~300% (30s), compared to the baseline. The measurements for particles less than 10 nm had a huge uncertainty. The particle size distrbutions at 120s and 180s were close to the baseline with an error less that 10% in a size range of 10~140 nm.

6) A good repeatability of measurements was observed for the particles larger than 20 nm, which was 5~20% for DW derived particles and 2~5% for SW derived particles. The short scan time did not compromise the repeatability of measurements.

المستخلص :يهدف هذا العمل لقياس تأثير وقت المسح الضوئي لجهاز المسح على استقرار وتحويل قياس الجسيمات فائقة الدقة وجزيئات النانو. تم قياس الجسيمات الناتجة من الماء المقطر والماء المالح (0.020٪ بالوزن) بواسطة مولد الأيروسول لتركيزات العدد وتوزيعات الحجم باستخدام SMPS. تم ضبط وقت مسح الجهاز على 30 و 60 و 120 و 180 و 240 ثانية. بالإضافة الي ذلك تم استخدام الهواء المضغوط المرشح في النفخ عبر المولد لإنتاج جزيئات. تمت مقارنة تأثير وقت المسح على أعداد الجسيمات وتوزيعات الحجم لكل حالة. تم العثور على توزيع الحجم الأحادي للجزيئات في جميع الظروف التي تم فحصها. أظهرت النتائج حدوث تحول في توزيع حجم الجسيمات نحو الجسيمات الأصغر وتركيزات أقل من الجسيمات مع أوقات مسح أقصر مثل 30و60 تانية مشيرا إلى أن وقت المسح يؤثر على عدد الجسيمات وقياسات توزيع الحجم. لخصت الدراسة انه يجب أن يختار وقت المسح للجهاز علي أن يكون أكثر من 100 ثانية للحصول على نتائج موثوقة بشكل معقول.

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