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On the Effects of Urea and Water Injection on Particles across the SCR Catalyst in a Heavy - Duty Euro VI Diesel Engine

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Abstract

Particle emissions from heavy-duty engines are regulated both by mass and number by Euro VI regulation. Understanding the evolution of particle size and number from the exhaust valve to the tail pipe is of vital importance to expand the possibilities of particle reduction. In this study, experiments were carried out on a heavy-duty Euro VI engine after-treatment system consisting of diesel oxidation catalyst, diesel particulate filter and selective catalytic reduction (SCR) unit with AdBlue injection followed by ammonia slip catalyst. The present work focusses on the SCR unit with regard to total particle number with and without nucleation particles both. Experiments were conducted by varying the AdBlue injection quantity, SCR inlet temperature [to vary the reaction temperature], exhaust mass flow rate [to vary the residence time in SCR], and fuel injection pressures [to vary inlet particle number and

inlet NO_x]. Sampling for particle measurements was performed at the inlet, upstream of the urea injector and the outlet of the SCR. Particle measurements were made using two different two-stage dilution systems, for measuring non-volatile and volatile particles, respectively. The total particle number (PN) was measured using two different condensation particle counters (CPC), one with the cut-off size at 23nm and another with a cut-off size at 7 nm to capture nuclei mode particles. An increase in the total number of particles was observed at 400°C and 1200 bar of fuel injection pressure with the higher AdBlue injection quantities compared to the dry-run SCR. At 400°C, a surge in nucleation occurs irrespective of the fuel injection pressures. An experiment was also made to isolate the water droplets effect on PN from nitrate formation. The SCR was injected with de-ionized water and a PN reduction was observed across the SCR and the reduction was higher with higher inlet PN to the SCR.

Introduction

Particle emissions are a concern in regard to air quality. Various studies [1, 2] have reported that particle emissions are affecting health. Internal combustion engine (ICE) is one of the primary emission sources for particles. Hence legislations have been laid on restricting particle emissions from ICEs. From Euro VI legislation for heavy-duty (HD) applications, regulation is in place for the total Particle Number (PN) emitted. For regulatory measurements, Particle Number (PN) emissions are measured using instruments complying with Particle Measurement Programme (PMP) requirements [3].

Particles emitted from diesel engines HD diesel engines is of interest in this work. Particles emitted by diesel engines are chain-like aggregates, consisting of primary particles with each particle aggregate containing many agglomerates and further connected to each other [4]. The particle size is larger if the agglomerates connected to the primary particles are more in number. Based on the size, particles can be classified into three groups viz.: nuclei mode (3–30 nm), accumulation mode (30–500 nm) and coarse mode (>1 μm) particles [5].

Formation of the particle core takes place during the combustion process in the engine giving rise to the primary particles which are in the nucleation mode, and the tail pipe emission of the particles depends on the type of the exhaust after-treatment system [6]. Each of the exhaust after-treatment devices handle selective emissions such as HC, CO, NO_x and particle emissions. The effect of each exhaust after-treatment device from the perspective of particle emissions could be of interest, as it improves the understanding of particle evolution along the exhaust system.

The exhaust after-treatment system for a Euro VI engine consists of several devices namely diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalytic reduction (SCR) unit. The present work focusses on the effect of SCR on PN emissions. There have been work on the effect of SCR on PN emissions reported in the literature as follows.

Thiruvengadam et al. [7] have noticed that when the exhaust entering the SCR had a temperature above 380°C, the urea-injected in SCR gives rise to nucleation mode particles (6–15 nm) both in steady-state and transient cases while no

increase was seen at lower exhaust temperature operation points. The experimental study was conducted on a turbo-charged heavy-duty Euro IV diesel engine. The after-treatment system contained DOC+DPF+SCR+Ammonia Slip Catalyst (ASC).

Pietikäinen et al. [8] have tested the effect of a stand-alone SCR unit on the particle emissions on a four-stroke non-road diesel engine. The effect of load (100%, 75%, 50%, and 25%) at constant speed (1500 rpm) was evaluated following ISO 8178 E2 cycle. From the results it was observed that on the whole, there was a reduction in PN for about 30% with the SCR. On the other hand, an increase in PN was observed among the nucleation particles. The portion of the emitted particles that were in the nucleation mode range (< 50 nm) increased from 35% to 47%. The study [8] discusses the effect of SCR in standalone operation and there might be influence of higher particle concentration as the experiment was without a DPF. The presence of a DPF could be closer to real world effect of SCR.

In another experimental study by Karjalainen et al. [9], a heavy-duty diesel off-road engine was tested for the effect of DOC+SCR unit on particle emissions in a transient cold-start cycle. Throughout the cycle the exhaust temperature entering the SCR was less than 250°C . It was noticed that the total PN reduction with non-volatiles across DOC+SCR was 50.8% and while the reduction across the DOC was 17.7% showing a decrease of about 33% in total non-volatile PN across the SCR. Simultaneously, the total PN reduction with volatiles across DOC+SCR was 95.7% and across the DOC it was 82.5% showing a decrease of 13.5% in total volatile PN across the SCR. In summary, the test was a transient cold-start cycle showing an effective PN reduction with SCR inlet temperatures up to 250°C .

Lee et al. [10] have tested the effect of SCR on a heavy-duty diesel engine with DOC+DPF+SCR+ASC as the exhaust after-treatment system. The test was performed in 13-mode (ESC) cycle. It was noted that the NO_x conversion efficiency with and without ASC was 80% and 53% respectively. The less NO_x conversion efficiency without ASC was due to the slip of NH_3 . PN was measured using a two-stage dilution system with an evaporation tube to remove the volatiles. It was noted that the evaporation tube temperature did not affect the PN which was attributed to the removal of volatile particles. An increase in PN of about 161% (in comparison to without and with urea injection) was noted at a 1:1 molar ratio of NH_3/NO_x . Furthermore, from Scanning Electron Microscope (SEM) images, grains of spherical unreacted urea particles (200 nm–1 μm) were observed at an SCR inlet temperature of 250°C . The PN increase across the SCR is of very high percentage value (161%) this may be due to high filtration efficiency of the DPF. Hence absolute change in PN across the SCR is of interest in the place of relative change. In addition to that, the possibility of influence of the sample conditioning on PN measurements can be ruled out by comparing two different sample dilution conditioning methods.

Amanatidis et al. [11] made an experimental study on a turbocharged light-duty (LD) Euro 4 diesel engine for the effect of SCR on particle emissions. The after-treatment system contained DPF+SCR without DOC and ASC. Experiments were performed at constant speed with two different loads to analyze the effect of excess NH_3 levels at the SCR. For this

purpose, liquid NH_3 was injected in excess before the SCR instead of the urea-water solution (AdBlue) such that the concentration of NH_3 was 100 ppm after the SCR. The exhaust temperature at the inlet of SCR was 300°C (low load) and 400°C (high load) respectively. Increase in non-volatile particles 26–136% (<23 nm) and 80–193% (>23 nm) was observed over the SCR. It was noted that ammonium nitrate, ammonium sulphate as well as ammonium chloride particles were formed in the SCR. The experimental study [11] measured the effect of inlet temperature with liquid NH_3 injection before the SCR instead of the urea-water solution. The same experiment in a HD engine of a commercial truck with urea-water injected SCR will be close to real application. Also different inlet NO_x values to the SCR is needed to be investigated.

In literature as described above, most studies were conducted in transient and stationary cycle operation of the engine. An analysis at steady state operating conditions of the engine would show more light on the PN change across the SCR. The effect of the mass flow rate through the SCR was not reported in literature and hence it was of interest to be analysed. Also, literature reports higher PN emissions at higher temperatures (above 380°C) [7]. So, an analysis on the low and high temperature of the SCR for the comparison of the temperature could be of interest. These higher temperatures at the SCR is mostly observed in HD Engines. Thus the present work was framed to study the effect of the SCR on PN emissions with various SCR inlet conditions using a HD Euro VI engine. In addition, effect of the dilution systems used for measuring PN may influence the measurement. Thus, a comparison between two different sample dilution conditioning methods could rule out the effect of the dilution systems used for measuring PN across the SCR. Hence, one dilution system in compliance with PMP regulation (as a reference) and other dilution system with different principle of dilution were the candidates for comparison. Furthermore, the change in PN with AdBlue injection was compared with deionized water injection to isolate the effect of urea and deionized water as these are the constituents in AdBlue solution. Increase in AdBlue injection quantity and its effect on the PN increase was analyzed with different inlet conditions to the SCR.

The hypotheses were framed with the SCR as a system of interest and are expressed as follows.

- Higher urea injection quantities to the SCR increase the salt formation as the concentration of ammonia increases.
- Higher temperatures at the SCR inlet due to higher engine loads will aid the reaction for salt formation due to high reaction temperatures leading to higher PN.
- Higher mass flow rates through the SCR may result in lesser residence time and may result in lesser number of particle emissions as the space velocity of the exhaust is higher.
- Higher fuel injection leads to higher NO_x and lesser PN from the engine. So higher SCR inlet NO_x concentration may favour the salt formation in turn leading to higher increase in PN across the SCR.
- With deionized water the NO_x reduction will be unchanged and thus there may not be particle

increase across the SCR. On the other hand there could be PN reduction as the water droplets dry up after sticking many particles.

Objectives

The objective of this work is to evaluate the effect of various inlet conditions on the particle number concentration and size distribution in a selective catalytic reduction (SCR) unit of a Euro VI HD diesel engine in steady state operation. The parameters swept in the experiment were (i) urea injection quantity (ii) the temperature at the SCR inlet, (iii) the exhaust mass flow rate and (iv) the particle number concentration/ NO_x at the SCR inlet.

Experimental Setup

The experiments were performed in a 6-cylinder Euro VI HD Diesel engine with a constant geometry turbocharger. The specifications of the engine are shown in Table 1. The exhaust treatment systems of the engine were DOC, DPF, SCR and ASC unit. An electrical dynamometer was used to load the engine. The engine was run on commercially available Swedish low sulphur S10 diesel.

Sampling

The measurements were taken at pre SCR and post ASC as shown in Figure 1, noted as inlet (1) and outlet (2). The measurements made were total PN, NO_x and temperature.

TABLE 1 Specifications of the engine

Engine	Scania D13
Bore	130 mm
Stroke	160 mm
Connecting Rod	255 mm
Compression ratio	18:1
Number of Cylinders	6 (In-line)
After Treatment system	DOC+DPF+SCR+ASC
Power	490 hp (365 kW)

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Particle measuring probe used was of multi-hole type [12]. The inlet and outlet sampling lines to the (SCR+ASC) unit were connected to a switching valve made from two temperature resistant ball valves so that the sample flow is not disturbed. The outlets of the valves were combined into a single line to connect to the sample inlet of the instrument. The total length of the sampling line (stainless steel) used from the point of measurement to the primary diluter was 2.3 m. The residence time from the point of measurement to the primary dilution was 0.78 s which is within the limits (≤ 3 s) of PMP [12]. The sampling conditions and length of the transfer line were kept the same at location 1 and 2.

NO_x measurements were taken at locations 1 and 2 using the engine NO_x sensor at 1 Hz data logging frequency for 120 seconds. Yttrium-stabilized Zirconia based electrochemical NO_x sensor with the measurement range of 0–3000 ppm and with an accuracy of 15–20% of real value was used. The sensor have no cross sensitivities (e.g. to CO, HC, O_2 , CO_2 or H_2O) but the sensor is cross sensitive to NH_3 . As the inlet measurement was made before the AdBlue injection and outlet measurement was made after the ASC, the error due to ammonia is minimised. Temperature measurements were also made at locations 1 and 2.

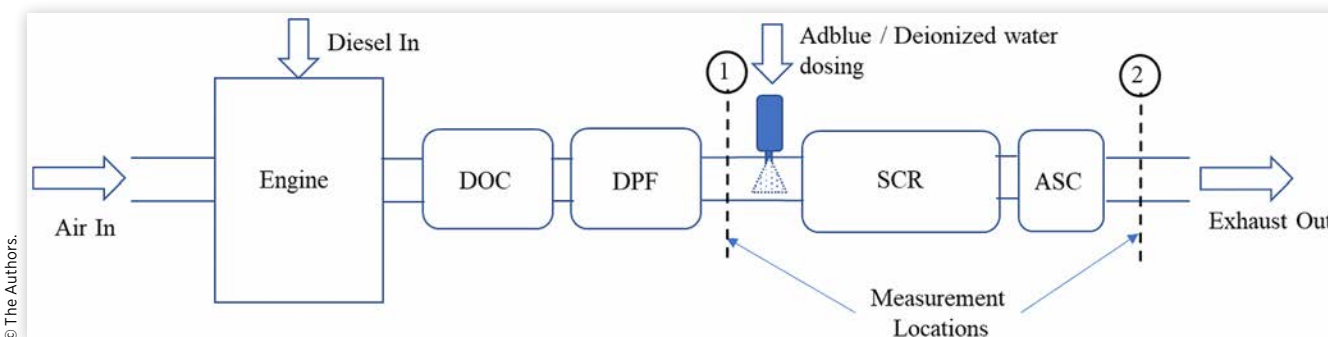
Particle Measurement System

The total particle number emissions were measured using two different dilution systems. One is a two-stage PMP compliant dilution system (DS1) with an evaporation tube and the other is a two-stage ejector dilution system (DS2). The schematic of the particle measurement system is shown in the overall experimental setup in Figure 2.

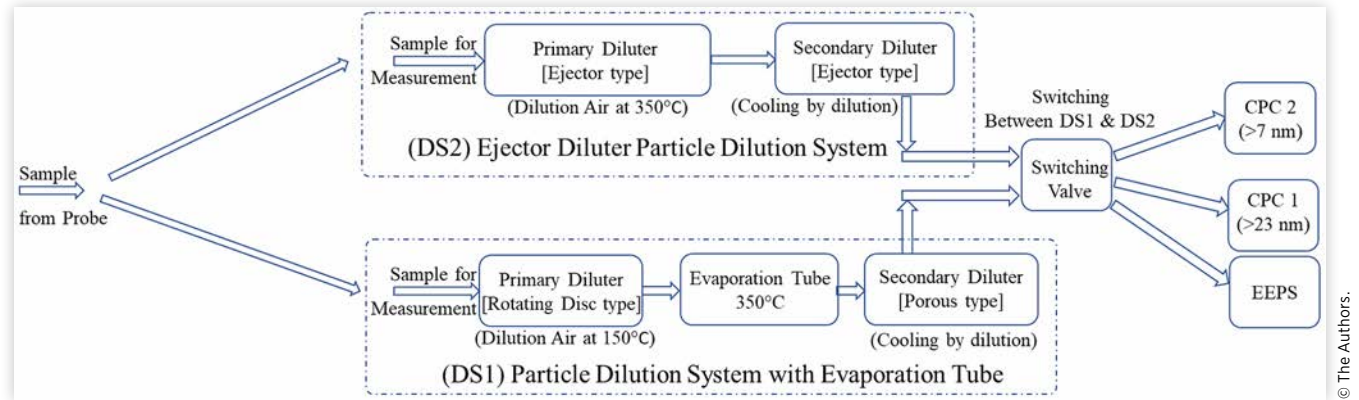
DS1 is a two-stage dilution system with an evaporation tube maintained at 350°C to measure non-volatile particles. The Primary diluter is a rotating disk type diluter and the secondary diluter is a porous type diluter. Primary dilution is a heated dilution at 150°C and secondary dilution is a cooling dilution. A 1.5 m heated hose maintained at 150°C was used after the primary diluter.

DS2 is a two-stage dilution system where the primary and the secondary diluter both are of ejector type. Primary dilution is a heated dilution at 350°C to measure non-volatile particles and secondary dilution is a cooling dilution. A 1.5 m heated hose maintained at 150°C was used at the inlet of the primary diluter.

FIGURE 1 Overall schematic diagram of the experimental setup



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FIGURE 2 Schematic diagram of the particle measurement system

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The primary dilution factor was 10 and secondary dilution factor was 15 for both the dilution systems. The outlet of both the instruments was connected to two condensation particle counters (CPC) with a switching valve. First CPC (CPC1) has a cut-off size of 23 nm. This is to measure the total PN from accumulation mode particles and further larger particles. The second CPC (CPC2) has a cut-off size of 7 nm. This is to measure the total PN from nucleation mode particles and further larger particles. All the particle number measurements reported with both the CPCs were corrected for dilution factors.

For each engine operating point, measurements were taken for three sampling periods to ensure repeatability. While measuring with the CPCs, each sampling period was 120 seconds, at 1 Hz measurement and data logging frequency.

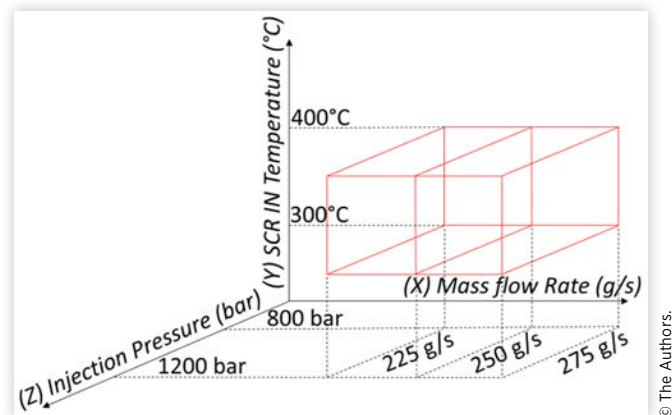
The particle size distribution was measured using the EEPS (Engine Exhaust Particle Sizer Spectrometer). The size distribution measured by the EEPS is in the range of 5.6 nm to 560 nm. The excess output from the dilution system DS1 was used as the conditioned sample inlet for EEPS. EEPS measurement was made without the dilution factor correction. As dilution factor is constant throughout the experiments, it affects the distribution only by a constant multiplication value. In the case of the particle size distribution measurement, each trial was 120 seconds at 10 Hz measurement and data logging frequency using the EEPS.

of 25 g/min. AdBlue injection was increased until the NO_x at the SCR outlet (SCR OUT NO_x) was fully reduced. The temperatures evaluated at the inlet of the SCR (SCR IN temperature) were 300°C and 400°C. The evaluated exhaust mass flow rates through the SCR were 225 g/s, 250 g/s and 275 g/s. These have been denoted in Figure 3. Hence in this study, SCR is the system of interest and the design of the experiments was with respect to the SCR and not the engine conditions. The total PN was varied by altering the injection pressures. In addition, it is to be noted that not only the PN but also NO_x out of the engine varies with injection pressures [13,14]. Higher the injection pressure, lesser is the total PN emission [13] and higher is the NO_x emission [14]. At lower injection pressures it is the vice versa. Thus experiments were performed at same operating points of SCR IN temperature and exhaust mass flow rates across the SCR with different fuel injection pressures namely 800 bar and 1200 bar. Hence a total of 12 operating points were performed in this experimental campaign.

To evaluate the effect of deionized water on the SCR system, the operating points of exhaust flow rate of 225 g/s for SCR IN temperatures of 300°C and 400°C; and fuel injection pressures 800 bar and 1200 bar were chosen since these points have the most residence time. Deionized water was injected through the urea dosing system (same as urea injection quantities in steps of 25 g/min).

Methodology

The experiments were performed on a Euro VI HD engine. The control for the wastegate of the turbocharger was disengaged throughout the experiments. Also, the exhaust brake was not used. At all operating points, fuel was injected at TDC. Experiments were designed to sweep the SCR inlet conditions to affect the particle formation. The exhaust conditions considered here were urea injection quantities, temperature at the inlet of the SCR, exhaust mass flow rate through the SCR, and particle concentration/ NO_x at the inlet of the SCR. Urea quantity injected to the SCR was varied by varying the rate of AdBlue (32.5% Urea+ deionized water) injection. AdBlue was injected through the urea dosing system in steps

FIGURE 3 Design of Experiments

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The experiments were conducted by varying the speed and torque of the engine, causing to vary the exhaust conditions. The speed was initially fixed and then the torque was increased so that the SCR IN temperatures was maintained constant. Later, the speed was increased and the process was repeated for higher flow rates of the exhaust. The order of the operating point's execution was in the order of DPF filling, leading to lesser particles at the inlet of SCR as the experiment progresses. Hence first, experiment was conducted for higher SCR IN temperature (400°C). At higher SCR IN temperature, the injection pressure was swept from higher to lower value because the engine out particles increases with lower injection pressure as explained earlier. Then lower to higher flow rates were swept.

Higher exhaust temperature causes regeneration of the DPF [15]. On the other hand, increasing flow rates cause an increased soot loading of the DPF [15]. Similarly, the same order was repeated for the lower SCR IN temperature (300°C) to have less particles from the regeneration of the DPF. The exhaust flow rate was calculated as the sum of mass flow rate of air and diesel ($\dot{m}_{\text{air}} + \dot{m}_{\text{diesel}}$).

In Figure 3, along the constant SCR IN temperature line, operating points analyzed in the direction of x-axis describes the effect of mass flow rate. Similarly, along a constant mass flow rate line, operating points are analyzed in the direction of y-axis describes the effect of SCR IN temperature. All measurements at each operating point were performed at steady state of engine operation.

Data Analysis

In these experiments, NO_x and PN measurements were made at inlet of the SCR (1) and outlet of the ASC (2) as shown in Figure 1. The change in NO_x between inlet and outlet with respect to inlet (in %) was calculated as shown in Equation (1).

$$\text{Change in NO}_x (\%) = \frac{\text{Outlet NO}_x - \text{Inlet NO}_x}{\text{Inlet NO}_x} \cdot 100 \quad (1)$$

The change in total PN between inlet and outlet with respect to inlet (#/cm³) was calculated as shown in Equation (2).

$$\text{Change in PN} = \text{Outlet PN} - \text{Inlet PN} \left(\# / \text{cm}^3 \right) \quad (2)$$

Change in PN is positive when there is an increase in the total number of particles across the SCR; on the other hand if the value is negative then there is a decrease in the total number of particles across the SCR. The change in PN was made as difference between outlet PN and inlet PN. The change was not made as percentage because the inlet PN value depends on the loading of the DPF. Each measurement was taken for three sampling trials. Each trial was taken for 120 seconds at 1 Hz frequency as described earlier. Thus, each engine operating point had 360 measurement points. All three trials were merged and averaged for the actual PN for each operating point. The PN values from CPC1 substituted in equation (2) was used to calculate the results for change in PN (>23 nm). The difference in PN values of CPC2 and CPC1 yields the PN (7-23 nm). Later, it was substituted in equation (2) was used to calculate the results for change in PN (7-23 nm).

Results

The results from the experiments are described here under three headings namely:

- NO_x reduction across the SCR.
- Change in PN across the SCR on accumulation mode particles and further (particle size >23 nm).
- Change in PN across the SCR on nucleation mode particles (particle size between 7-23 nm).

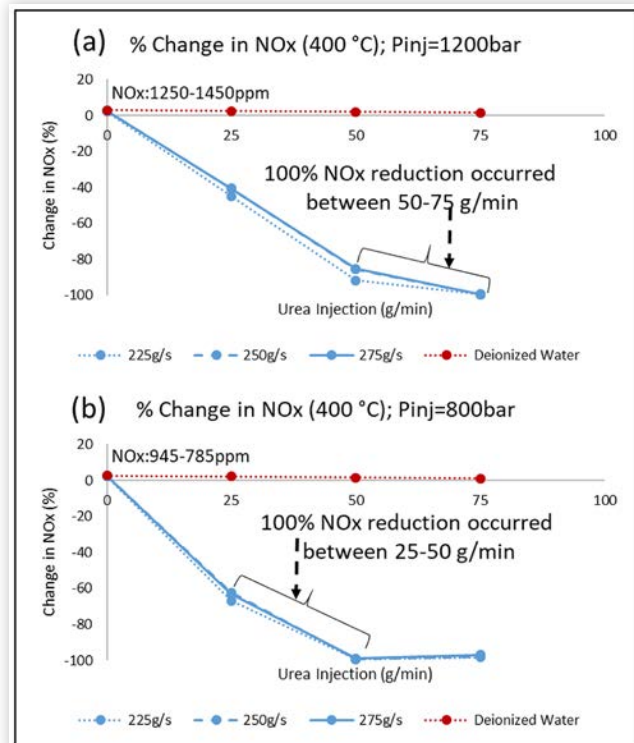
All measurements across the SCR denotes the measurements across the SCR including the ASC and henceforth mentioned as measurement across SCR.

NO_x Reduction across the SCR

First, an analysis was made to evaluate the change in NO_x (%) emission across the SCR at different operating conditions. The values are negative as there is an effective reduction of NO_x concentration across the SCR. Hence the term NO_x reduction is also used for the change in NO_x (%) emission across the SCR.

The results of the NO_x emission reduction across the SCR at 400°C with fuel injection pressure 1200 bar and 800 bar is given in Figure 4a and Figure 4b. The lowest and highest values of raw NO_x emission for the three flow rates is given as a range near the no urea injection point (0 g/min) near the x-axis for better understanding. The variation of urea injection was made in steps of 25 g/min, and hence 100% NO_x reduction can be confirmed only in terms of the same step value. From

FIGURE 4 Change in NO_x (%) across the SCR at 400°C



the figures it can be observed that the NO_x emission reduces as the urea quantity is increased. Almost insignificant NO_x reduction was observed at no urea injection (dry run SCR). Furthermore, comparing [Figure 4a](#) and [Figure 4b](#) it can be noticed that 100% NO_x reduction occurred between 50–75 g/min at 1200 bar fuel injection pressure whilst the same was observed between 25–50 g/min at 800 bar. As described earlier in the methodology, higher fuel injection pressure results in higher engine out NO_x emission. Hence the urea requirement needed for complete NO_x reduction was lower at 800 bar than at 1200 bar. (see [Figure 4a](#) and [Figure 4b](#)). In addition, the exhaust flow rate through the SCR does not seem to affect the NO_x reduction as all the blue lines almost merged with each other (see [Figure 4a](#) and [Figure 4b](#)). From the red dotted line in [Figure 4a](#) and [Figure 4b](#), it is evident that there is no change in NO_x emission across the SCR when operated with deionized water.

[Figure 5a](#) and [Figure 5b](#) shows the NO_x reduction at SCR IN temperature of 300°C with fuel injection pressure of 1200 bar and 800 bar. The lowest and highest values of raw NO_x emission for the three flow rates is given as a range near the no urea injection point (0 g/min) near the x-axis for better understanding. From [Figure 5a](#) and [Figure 5b](#), it can be seen that the urea injection quantities was made up to 50 g/min as the 100% NO_x reduction was reached within this value. As a result of the lower exhaust temperature (300°C), the NO_x emission from the engine was lower as the engine loads were lower in comparison to the loads at exhaust temperature of 400°C. Hence the urea injection quantity needed for NO_x reduction was lower when compared with urea injection quantity at 400°C. A comparison between [Figure 5a](#) and

[Figure 5b](#) shows that 100% NO_x reduction occurred between 25–50 g/min at 1200 bar (fuel injection pressure) whilst the same was observed between 0–25 g/min at 800 bar (fuel injection pressure). Similar to the observation at 400°C, from [Figure 5a](#) and [Figure 5b](#), it can be clearly observed from the red dotted line that there is no change in NO_x emission across the SCR when operated with deionized water.

Change in PN across the SCR on Accumulation Mode Particles and Further (Particle Size >23 nm)

The change in PN (>23 nm) across the SCR was measured to study the accumulation mode particles and particles further in size. The change in PN across the SCR is shown in absolute number difference between the outlet PN and inlet PN as calculated using [Equation \(2\)](#).

The results with respect to the change in PN (>23 nm) across the SCR in [Figure 6](#). Within [Figure 6](#), sub-figures a, b and c corresponds to the change in PN at 1200 bar across the SCR at different flow rates; sub-figures d, e and f corresponds to the change in PN at 800 bar across the SCR at different flow rates. Each sub-figure shows the effect of urea injection on PN (>23 nm) at two different temperatures.

For the flow rate of 225 g/s, results are shown with the deionized water injection using solid and dashed red-lines (see [Figure 6a](#) and [Figure 6d](#)).

From [Figure 6a](#), [Figure 6b](#) and [Figure 6c](#) it can be clearly seen that at an SCR IN temperature of 400°C, there is a PN increase of about $2 \cdot 4e+4 \text{ \#/cm}^3$ across the SCR with higher urea injection quantities. With the same urea injection quantities, at 300°C, the increase was less in magnitude. This could be due to the salt formation in SCR at high temperatures as discussed earlier. Furthermore, the increase in PN was not observed when there is no urea injection (0 g/min). Cutting across different exhaust flow rates in [Figure 6](#) (comparing sub figures a, b and c; comparing sub figures d, e and f) no clear trend was noticed. The above findings could be confirmed as it was observed with both the dilution systems, DS1 and DS2.

[Figure 6a](#) shows that the effect of deionized water injection at 1200 bar and shows no change in PN across the SCR at 400°C. Contrary to urea injection, with deionized water, there was neither an increase nor a decrease in PN noticed across the SCR at 400°C. At the same time, there was a reduction (of about $1e+4 \text{ \#/cm}^3$) in PN observed at 300°C. The water droplet stays longer than at 400°C causing particles to stick together and later drying with particles sticking together which in turn reduces the PN concentration at the outlet of the SCR.

From [Figure 6a](#), [Figure 6b](#) and [Figure 6c](#) it can be noted that the trends of the all curves with DS2 is similar to that of DS1. It can as well be noted that DS2 was always under valuing the PN when compared to DS1 but still it was closer to the PN values of DS1. The exception is at the higher urea injection values.

FIGURE 5 Change in NO_x (%) across the SCR at 300°C

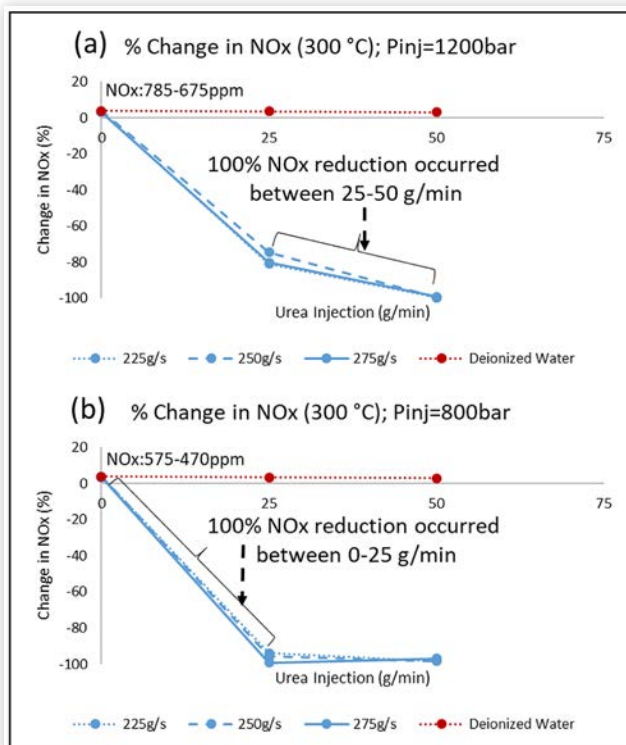
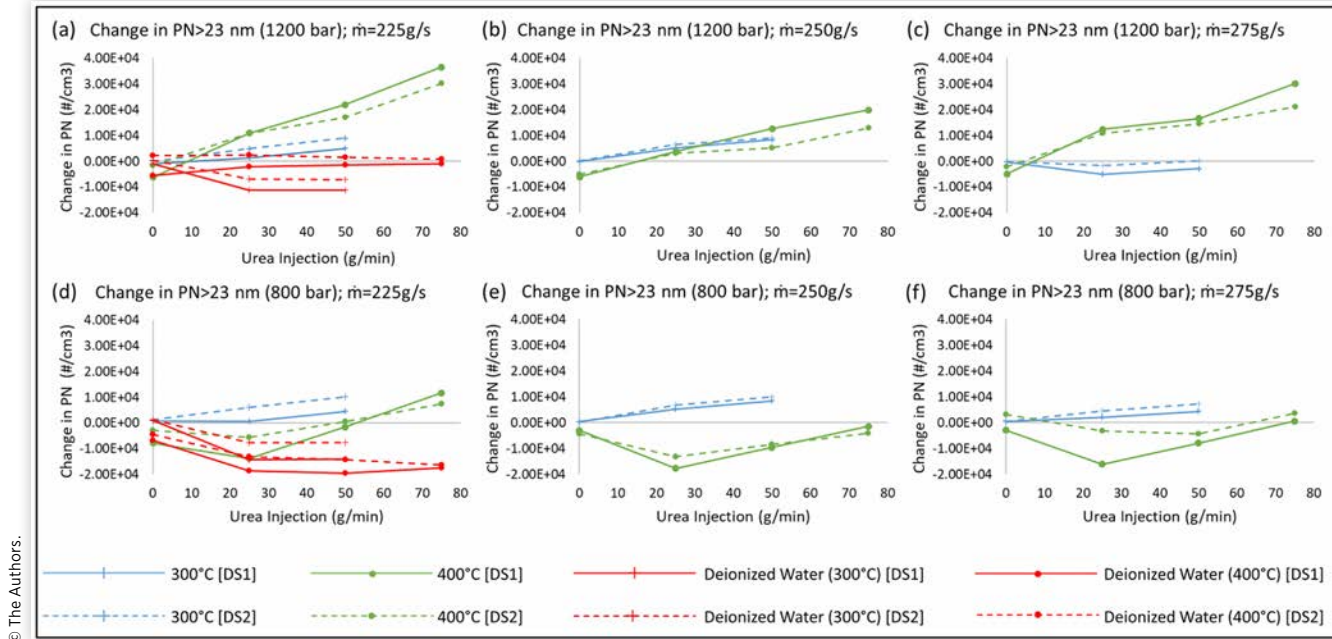


FIGURE 6 Change in PN>23 nm (#/cm³) across the SCR

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The analysis for PN (>23 nm) with respect to injection pressure 800 bar is presented as follows. From the results shown in [Figure 6d](#), [Figure 6e](#) and [Figure 6f](#), it can be noted that the increase in PN was not observed with SCR IN temperature of 400°C, in spite of same urea injection quantities. On the other hand, a decrease in PN of about $2e+4$ #/cm³ was noticed with urea injection and with a further increase, the reduction in PN decreased. This might be due the water droplets reducing the inlet PN to SCR since there could be greater regeneration of the DPF at 400°C. The reason is higher amounts of soot particles entering the DPF also get emitted as compared to 1200 bar. With excess urea, salt formation might increase. Whereas at 300°C, the same condition was not observed and DPF could be clogged. Hence there was a less pronounced increase with SCR IN temperature of 300°C.

The effect of deionized water injection at 800 bar is shown [Figure 6d](#). SCR inlet PN is higher at 800 bar and 400°C in comparison to the 1200 bar and 400°C due to higher engine out emissions [13]. Hence, the PN reduction was observed due to the water droplets effect. The droplets could be with deionized water causing to reduce the PN at the outlet of SCR. Hence, the magnitude of reduction of PN was higher when compared to 1200 bar (see [Figure 6a](#) and [Figure 6d](#)). Furthermore, the reduction in PN at 800 bar observed at SCR IN temperatures of 300°C was similar to 1200 bar. The reason could be lesser particles at SCR inlet due to lesser regeneration of the DPF and more clogged at 300°C.

The results with respect to fuel injection pressure 800 bar using dilution systems DS1 and DS2 were similar (see [Figure 6d](#), [Figure 6e](#) and [Figure 6f](#)). By comparison it can be noticed that the difference between DS1 and DS2 was in the magnitude of PN.

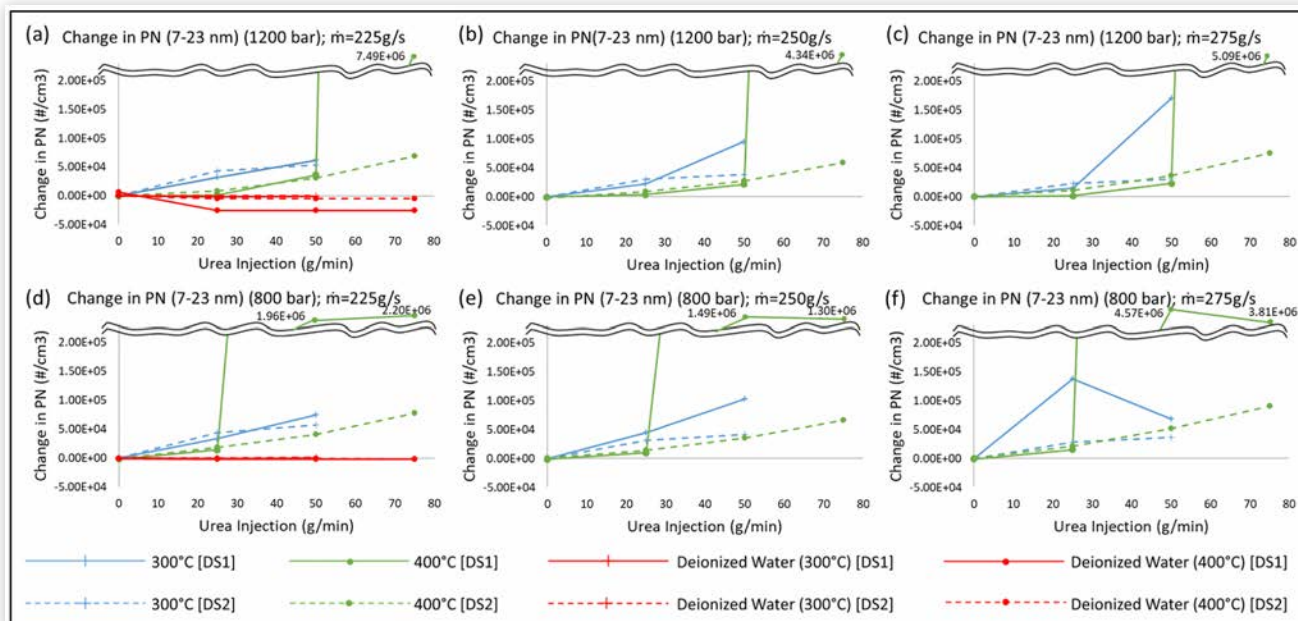
Change in PN across the SCR on Nucleation Mode Particles and Further (7–23 nm)

The analysis for PN (7–23 nm) was made to analyse the nucleation particles. The change in PN (7–23 nm) was calculated by the difference in PN values of CPC2 and CPC1 yielding the PN (7–23 nm) values. Later, the values were substituted in [equation \(2\)](#) to calculate the results for change in PN (7–23 nm) as explained in data analysis section.

The results with respect to the change in PN (7–23 nm) across the SCR in [Figure 7](#). Within [Figure 7](#), sub-figures a, b and c corresponds to the change in PN at 1200 bar across the SCR at different flow rates; sub-figures d, e and f corresponds to the change in PN at 800 bar across the SCR at different flow rates. Each sub-figure shows the effect of urea injection on PN (7–23 nm) at two different temperatures. The graphs have a y-axis to fit the extreme value points. The extreme points are shown by values in data labels.

For the flow rate of 225 g/s, results are shown with the deionized water injection using solid and dashed red-lines (see [Figure 7a](#) and [Figure 7d](#)).

From [Figure 7a](#), [Figure 7b](#) and [Figure 7c](#) it can be evidently seen that at an SCR IN temperature of 400°C and injection pressure of 1200 bar, the magnitude of change in PN showing a sudden increase in PN of nucleation particles across the SCR beyond urea injection quantity of 50 g/min which corresponds to 100% NO_x reduction (see [Figure 4a](#)). On other hand, with the same urea injection quantities, at 300°C such sudden increase was not observed. As the increase was drastic for SCR IN temperature of 400°C, the scale of y-axis was very high making the 300°C curve to trail near the x-axis. Also, there

FIGURE 7 Change in PN (7–23 nm) (#/cm³) across the SCR

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was gradual increasing trend observed in PN across the SCR at urea injection quantity up to 50 g/min.

With different exhaust flow rates in Figure 7 (comparing sub figures a, b and c; comparing sub figures d, e and f) no clear trend could be noticed and hence can be confirmed as it was observed with both the dilution systems, DS1 and DS2.

In Figure 7, the solid and dotted lines indicate the PN measurements with DS1 and DS2 respectively. From Figure 7 (comparing sub figures a, b and c; comparing sub figures d, e and f) it can be seen that the sudden increase in PN was not observed using the DS2 and instead a gradual increasing trend was observed at 400°C with higher urea injection quantities. This could be due to the sample conditioning differences between the dilution systems DS1 and DS2. There could be volatile components after primary dilution in DS2 and then coagulation of the particles due to the absence of evaporation tube causing a lesser increase in PN measurements.

Figure 7a shows the effect of deionized water injection at 1200 bar. The results show a reduction on PN of nucleation particles (of about $3e+4$ #/cm³) while the SCR was operated at 400°C with deionized water. This could be because of regeneration of DPF and particles emitted from the DPF. The engine out particles from 1200 bar are smaller than at 800 bar [13] and hence the regenerated particles could also be smaller and got noticed in PN (7–23 nm) measurements. This was not noticed at 300°C as the DPF regeneration could be less. The reason for reduction could be the droplets sticking to particles in the SCR.

The analysis for PN (7–23 nm) with respect to injection pressure 800 bar is presented in Figure 7d, Figure 7e and Figure 7f. It can be clearly seen that at an SCR IN temperature of 400°C and injection pressure of 800 bar, the magnitude of change in PN shows a sudden increase across the SCR beyond urea injection quantity of 25 g/min. It can be recollected from Figure 4b that it corresponds to 100% NO_x reduction. Hence the sudden increase at 400°C using DS1 matches with excess urea injection quantities. Conversely, the sudden increase in

PN was not observed with SCR IN temperature of 300°C, in spite of same urea injection quantities. Also, there was a gradual increasing trend observed in PN across the SCR up to the urea injection quantity of 50 g/min.

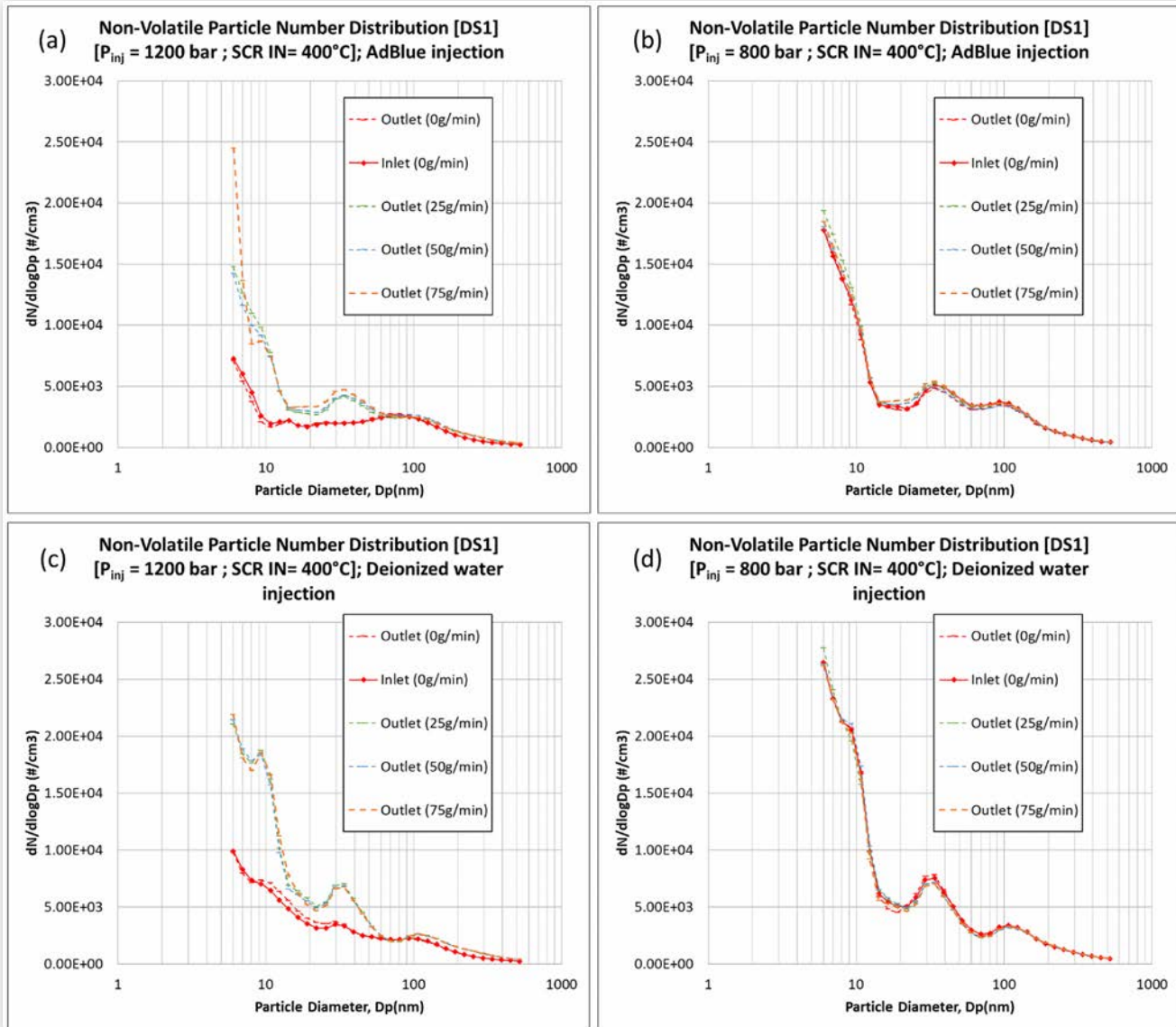
Figure 7d shows the change in PN with regard to nucleation particles at 800 bar compared with deionization water injection. No reduction in nucleation PN with deionization water injection was noticed. This could be due to lesser nucleation particles emitted from the engine at 800 bar when compared to 1200 bar, and, also due to higher PN to DPF, trapping the nucleation particles in the DPF.

The measurements with the EEPS is presented for 400°C in Figure 8. Particle Number distribution with AdBlue injection is shown in sub-plots a and b. Particle Number distribution with deionized water injection is shown in sub-plots c and d. From Figure 8a, it can be observed that at 1200 bar of fuel injection pressure, with urea injection, particle increases both in nucleation and accumulation. On the other hand, higher urea quantities did not continually increase the particles. Surprisingly, particle increase was seen with the EEPS when using deionized water but is not corroborated by the CPC measurements particle increase was noticed. Figure 8b and Figure 8d shows no change in particles across the SCR with fuel injection pressure of 800 bar.

It is possible that the inbuilt soot inversion matrix in EEPS was not capturing the particle change across the SCR appropriately as these are salt particles. So further conclusions could not be drawn from the EEPS results.

Discussion

An experiment testing the effect of various inlet conditions of SCR was performed and the results were presented and the inferences are made from the results as follows.

FIGURE 8 Particle Number distribution at 400°C with AdBlue and deionized water injection

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Higher urea injection quantities to the SCR increase the salt formation as the concentration of ammonia increases and the results confirm the increase in PN across the SCR using both the dilution systems.

Higher temperatures at the SCR inlet are due to higher engine loads and aid the reaction of ammonium salt formation due to high reaction temperatures [11]. The accelerated salt formation rate was leading to higher PN at SCR outlet but the finding cannot be generalized as it depends on the inlet NO_x concentration to the SCR. Excess urea injection events at 400°C lead to drastic increase of nucleation PN. Only DS1 could measure this phenomenon and the reason is unclear. One possible reason could be the presence of evaporation tube in DS1, ensures non-volatile nucleation particles to be distinct for measurement, while in DS2, the nucleation particles was not be dry enough after dilution and may have coagulated before measurement [16]. The particles could be salts or unreacted urea [10,11].

Higher mass flow rates through the SCR had little effect on NO_x reduction. This led to the inference that the residence time and space velocity was not affecting the NO_x conversions at higher temperatures (300°C and 400°C), which was also noted by Han et al. [17]. The same was reflected in the PN change across the SCR, i.e., residence time and space velocity had little or no influence in PN change across the SCR, at exhaust temperatures of 300°C and 400°C.

Higher fuel injection pressures led to higher NO_x and lower PN from the engine, so higher SCR inlet NO_x concentration may favour nitrate salt formation, in turn leading to higher increase in PN across the SCR.

With deionized water injection in the SCR, NO_x was unchanged and PN increase was not observed as there was no ammonia to promote salt formation. On the other hand, deionized water led to PN reduction when the inlet PN is higher. This was observed when the temperatures was high and causing passive DPF regeneration. The resulting particles from DPF

TABLE 2 Inferences on change in PN (>23nm) across the SCR

Temperature (°C)	DS1	DS2	Net Conclusion
300°C	No significant change was observed with increase in urea injection quantities	No significant change was observed with increase in urea injection quantities	No significant change across the SCR with increase in urea injection quantities
400°C	Increase in PN observed with increase in urea injection quantities at 1200 bar	Increase in PN observed with increase in urea injection quantities at 1200 bar	At 1200 bar increase in PN across the SCR with increase in urea injection quantities
	No significant change was observed with increase in urea injection quantities at 800 bar	No significant change was observed with increase in urea injection quantities at 800 bar	No significant change across the SCR with increase in urea injection quantities at 800 bar

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TABLE 3 Inferences on change in PN (7-23 nm) across the SCR

Temperature (°C)	DS1	DS2	Net Conclusion
300°C	Increase in PN was observed with increase in urea injection quantities	Increase in PN was observed with increase in urea injection quantities	Increase in PN across the SCR was observed with increase in urea injection quantities
400°C	(i) Increase in PN was observed with increase in urea injection quantities	Increase in PN was observed with increase in urea injection quantities	Increase in PN across the SCR was observed with increase in urea injection quantities
	(ii) Sudden increase in PN was observed at excess urea injection quantities		

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enter the SCR. In the SCR many particles cling to water droplets and finally dry up together leading to lower particles. This effect got saturated with the water injection quantities and did not continually decrease with increased injection quantities.

Measurement of the particle number distribution using EEPS did not lead to any solid inferences as the inbuilt soot inversion matrix in EEPS was not capturing the particle change across the SCR appropriately. The reason could be due to the salt particles from the SCR instead of soot particles, so further conclusions could not be drawn from the EEPS results.

The inferences for the change in PN for particles >23 nm are shown in [Table 2](#).

The inferences for the change in PN for nucleation particles between 7–23 nm are shown in [Table 3](#).

Conclusions

The experiment investigated the effect of various inlet conditions of SCR on PN change across the SCR of a Euro VI HD engine. The conclusions are made from the results as follows.

An increase in PN across the SCR occurs at 400°C with higher urea injection quantities accompanied with higher inlet NO_x values due to the formation of nitrate salts. Otherwise, the higher temperature at the SCR inlet does not necessarily signify an increase in PN across the SCR. At the same time, an increase in nucleation particles was observed both at 300°C and 400°C with higher urea injection quantities, irrespective of the inlet NO_x values due to the formation of ammonium salts. Furthermore, a sudden increase was observed only at 400°C for excess urea injection events, irrespective of the inlet NO_x values due to the formation of ammonium salts or unreacted urea. This event was captured

only by the particle dilution system with an evaporation tube. On the other hand, with deionized water injection, there was no decrease in NO_x or increase in PN across the SCR as there was no ammonia to promote salt formation.

Flow rate across the SCR was not affecting the NO_x reduction and PN increase across the SCR at all presented cases as the space velocity has low effect on the reaction kinetics of urea in the SCR at higher temperatures (300°C and 400°C).

Appropriate particle number distribution measurements across the SCR was not captured by EEPS. The reason could be the in-built soot inversion matrix calibrated for soot particles while the particles from the SCR are salts.

Higher fuel injection pressures lead to increase in NO_x and decrease in PN from the engine. The increased engine-out NO_x is treated at the SCR but this treatment increases the PN thereby setting back the extent of the PN reduction attained in the engine leading to a NO_x – PN trade-off at high temperatures.

References

1. Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., et al., "Particulate Matter Air Pollution and Cardiovascular Disease: An Update to the Scientific Statement from the American Heart Association," *Circulation* 121(21):2331–2378, 2010, doi:10.1161/CIR.0b013e3181d8bec1.
2. Donaldson, K., Li, X.Y., and MacNee, W., "Ultrafine (Nanometre) Particle Mediated Lung Injury," *Journal of Aerosol Science* 29(5–6):553–560, 1998, doi:10.1016/S0021-8502(97)00464-3.
3. Giechaskiel, B., Mamakos, A., Andersson, J., Dilara, P., et al., "Measurement of Automotive Nonvolatile Particle Number

- Emissions within the European Legislative Framework: A Review,” *Aerosol Science and Technology* 46(7):719–749, 2012, doi:10.1080/02786826.2012.661103.
4. Wang, X., Wang, Y., Bai, Y., Wang, P., et al., “An Overview of Physical and Chemical Features of Diesel Exhaust Particles,” *Journal of the Energy Institute* 92(6):1864–1888, 2019, doi:10.1016/j.joei.2018.11.006.
 5. Kittelson, D.B., Watts, W.F., Johnson, J.P., Rowntree, C.J., et al., “Driving down On-Highway Particulate Emissions,” SAE Technical Paper 2006-01-0916, 2006, <https://doi.org/10.4271/2006-01-0916>.
 6. Rönkkö, T., Virtanen, A., Kannosto, J., Keskinen, J., et al., “Nucleation Mode Particles with a Nonvolatile Core in the Exhaust of a Heavy Duty Diesel Vehicle,” *Environmental Science and Technology* 41(18):6384–6389, 2007, doi:10.1021/es0705339.
 7. Thiruvengadam, A., Besch, M.C., Carder, D.K., Oshinuga, A., et al., “Influence of Real-World Engine Load Conditions on Nanoparticle Emissions from a DPF and SCR Equipped Heavy-Duty Diesel Engine,” *Environmental Science and Technology* 46(3):1907–1913, 2012, doi:10.1021/es203079n.
 8. Pietikäinen, M., Väliheikki, A., Oravisjärvi, K., Kolli, T., et al., “Particle and NO_x Emissions of a Non-Road Diesel Engine with an SCR Unit: The Effect of Fuel,” *Renewable Energy* 77:377–385, 2015, doi:10.1016/j.renene.2014.12.031.
 9. Karjalainen, P., Ronkko, T., Lahde, T., Rostedt, A., et al., “Reduction of Heavy-Duty Diesel Exhaust Particle Number and Mass at Low Exhaust Temperature Driving by the DOC and the SCR,” *SAE Int. J. Fuels Lubr.* 5(3):1114–1122, 2012, <https://doi.org/10.4271/2012-01-1664>.
 10. Lee, S., Cho, Y., Song, M., Kim, H., et al., “Experimental Study on the Characteristics of Nano-Particles Emissions from a Heavy-Duty Diesel Engine Using Urea-SCR System,” *International Journal of Automotive Technology* 13(3):355–363, 2012, doi:10.1007/s12239-012-0033-4.
 11. Amanatidis, S., Ntziachristos, L., Giechaskiel, B., Bergmann, A., et al., “Impact of Selective Catalytic Reduction on Exhaust Particle Formation over Excess Ammonia Events,” *Environmental Science and Technology* 48(19):11527–11534, 2014, doi:10.1021/es502895v.
 12. Giechaskiel, B., Arndt, M., Schindler, W., Bergmann, A., et al., “Sampling of Non-Volatile Vehicle Exhaust Particles: A Simplified Guide,” SAE Technical Paper 2012-01-0443, 2012, <https://doi.org/10.4271/2012-01-0443>.
 13. Wu, B.Y., Zhan, Q., Zhang, S.K., et al., “Effect of Heavy-Duty Diesel Engine Operating Parameters on Particle Number and Size Distribution at Low Speed Condition,” *Int J Automot Technol* 19(4):623–633, 2018, doi:10.1007/s12239-018-0059-3.
 14. Tan, X.G., Sang, H.L., Qiu, T., Fan, Z.Q., et al., “The Impact of Common Rail System’s Control Parameters on the Performance of High-Power Diesel,” *Energy Procedia* 16(PART C):2067–2072, 2011, doi:10.1016/j.egypro.2012.01.314.
 15. Guan, B., Zhan, R., Lin, H., and Huang, Z., “Review of the State-of-the-Art of Exhaust Particulate Filter Technology in Internal Combustion Engines,” *Journal of Environmental Management* 154:225–258, 2015, doi:10.1016/j.jenvman.2015.02.027.
 16. Kasper, M., “The Number Concentration of Non-Volatile Particles - Design Study for an Instrument According to the PMP Recommendations,” SAE Technical Paper 2004-01-0960, 2004, <https://doi.org/10.4271/2004-01-0960>.
 17. Han, J., Kim, J., Jung, H., Pyo, S., et al., “Improvement of NO_x Reduction Rate of Urea SCR System Applied for a Non-Road Diesel Engine,” *International Journal of Automotive Technology* 20(6):1153–1160, 2019, doi:10.1007/s12239-019-0108-6.

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Definitions/Abbreviations

ASC - Ammonia Slip Catalyst

CO - Carbon monoxide

CPC - Condensation Particle Counters

DOC - Diesel Oxidation Catalyst

D_p - Diameter of the particle

DPF - Diesel Particulate Filter

DS - Diesel System

EEPS - Engine Exhaust Particle Sizer Spectrometer

ESC - European Stationary Cycle

HC - Hydrocarbon

HD - Heavy-Duty

ICE - Internal Combustion Engines

ISO 8178 E2 - International Stationary engine testing cycle for marine application

LD - Light-duty

n - No. of Particles

NH₃ - Ammonia

NO_x - Oxides of Nitrogen

PMP - Particle Measurement Programme

PN - Particle Number

ppm - parts per million

SCR - Selective Catalytic Reduction unit

SCR IN - Inlet of SCR unit
SCR OUT - Outlet of SCR unit

SEM - Scanning Electron Microscope
TDC - Top Dead Centre

Appendix

Error Analysis for NO_x Measurements

The 95% confidence interval of the NO_x measurement was calculated using the expression shown below.

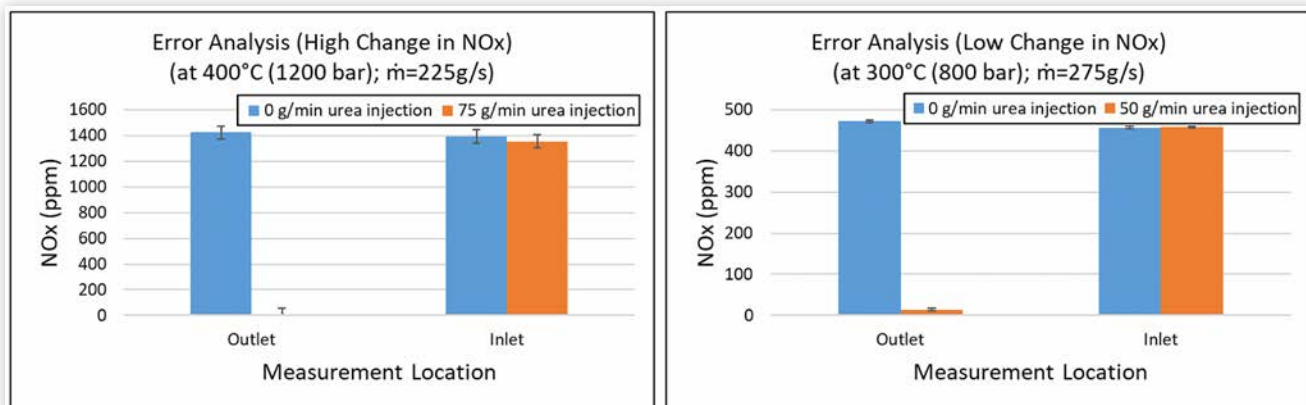
$$\text{Actual NO}_x (\text{ppm}) = \text{Mean value} \pm 1.96 \frac{\sigma}{\sqrt{N}}$$

Where,

σ - Standard deviation of the measurement; N - Number of samples

The number of samples taken at each location for each operating point is 120. The same was mentioned under the heading 'Sampling', "NO_x measurements were taken at locations 1 and 2 using the engine NO_x sensor at 1 Hz data logging frequency for 120 seconds."

Two sample points with high and low NO_x values are shown for the error analysis. In both the points NO_x measurements are shown with and without the urea injection for complete NO_x reduction. The high change point for NO_x is the point with 1200 bar fuel injection; SCR IN temperature 400°C; 0 and 75 g/min urea injection; $\dot{m} = 225$ g/s of exhaust flow. The low change point is the point with 800 bar fuel injection; SCR IN temperature 300°C; 0 and 50 g/min urea injection; $\dot{m} = 225$ g/s of exhaust flow.



From the inlet and outlet values of NO_x along with the error bars it can be seen that the change in NO_x across the SCR with urea injection is significant and outside the error bars.

Error Analysis for PN Measurements

The 95% confidence interval of the PN (>23 nm) measurement was calculated using the expression shown below.

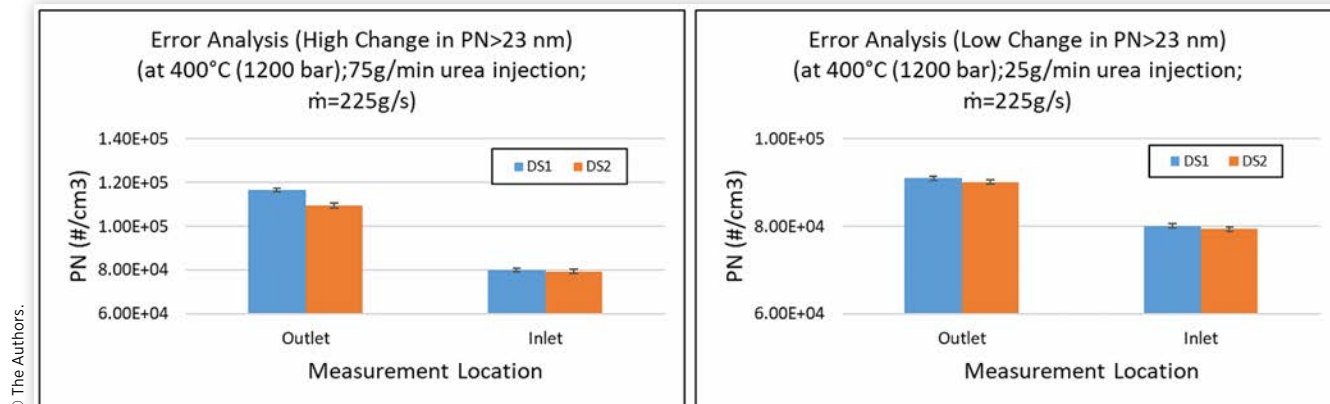
$$\text{Actual PN} (\# / \text{cm}^3) = \text{Mean value} \pm 1.96 \frac{\sigma}{\sqrt{N}}$$

Where,

σ - Standard deviation of the measurement; N - Number of samples

The number of samples taken at each location for each operating point is 360. The same was mentioned under the heading 'Particle Measurement System', "For each engine operating point, measurements were taken for three sampling periods to ensure repeatability. While measuring with the CPCs, each sampling period was 120 seconds, at 1 Hz measurement and data logging frequency".

Two sample points are shown for the error analysis for both the dilution systems DS1 and DS2. The sample point taken are for high and low change in PN (>23 nm) across the SCR. The high change point is the SCR IN temperature 400°C; 75 g/min urea injection; $\dot{m} = 225$ g/s of exhaust flow. The low change point is the SCR IN temperature 400°C; 25 g/min urea injection; $\dot{m} = 225$ g/s of exhaust flow. The 95% confidence interval of the measurement is shown below with the error bars which is barely visible. Hence the figure is scaled from 6e4 for clarity.



From the inlet and outlet values of PN along with the error bars it can be seen that the change in PN across the SCR with urea injection is significant and outside the error bars.

With regard to the change in PN (7–23 nm) across the SCR had a sharp spike in the measurements. The 95% confidence interval may not be visible in a plot and hence not presented here.