

Performance evaluation of a urea-water selective catalytic reduction (SCR) for controlling the exhaust emissions from a diesel engine

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Received 13.07.2009

Abstract

An integrated performance analysis of a vanadium-based urea-SCR system used for the reduction of exhaust emissions from a diesel engine was carried out. The engine was run on an AC electrical dynamometer in accordance with an 8-mode steady-state cycle. The number-size distribution of particles and carbonyls was analyzed using an electrical low pressure impactor (ELPI) and high performance liquid chromatography (HPLC), respectively. It was found that conversion and/or reduction efficiency (RE) of the SCR were highly affected by the catalyst temperature and space velocity (SV). The NO_x pollutants were greatly reduced with the decrease in SV within the load modes of cyclic speeds. The SCR exhibited an RE of more than 50% for NO_x emissions at 321-435 °C, while the maximum RE was 80.5%. Total hydrocarbon (HC) emissions were also increased with the decrease in load for both cyclic speeds, while the RE varied from 38.7% to 71.1%. Significant increases in upstream and downstream carbon monoxide (CO) emissions were noticed with the decrease in engine load. Reluctance to reduction or a negative RE, ranging from 1.5% to 72%, was observed for CO emissions with the SCR. In addition, nanoparticles were greatly reduced, whereas particles of the size range 57-255 nm showed less reduction. The number-size distribution of particles was shifted from smaller to larger sizes with the SCR retrofit. Furthermore, a substantial conversion of up to 55.3% was obtained in the case of carbonyl emissions. The maximum RE was 58%, 67%, 50%, and 64% for formaldehyde, acetaldehyde, acrolein and acetone, and propionaldehyde, respectively.

Key Words: Diesel engine, emissions, particulate matter, carbonyls, urea-SCR catalyst.

Introduction

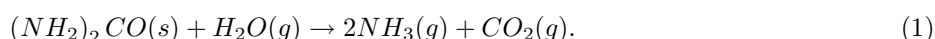
It is envisaged that the future emission levels for diesel engines will no longer be met merely by engine tuning. Additional efforts in the form of suitable advanced aftertreatment devices will be required to meet the stringent emission standards. The controlling of NO_x and particulate matter (PM) from diesel engines has always been a challenge for researchers due to ever tighter emission legislations. Reduction of NO_x and PM from diesel engine

exhaust through aftertreatment technology is interconnected as there is a trade-off between these pollutants (Ogunwumi et al., 2002). A number of possible techniques to overcome this dilemma are under consideration. For example, the engine can be set to give reduced PM and increased NO_x emissions, and then NO_x can be decreased with the use of SCR. Conversely, the engine can be calibrated to result in reduced NO_x and increased PM, and then the PM can be abated using continuously regenerating diesel particulate filter (CR-DPF) technology (Chandler et al., 2000). However, an optimized engine together with a urea-SCR system eliminates the need for a diesel particulate filter (DPF) even in complying with Euro V emission standards, thus reducing the complexity of the total system (Gekas et al., 2002).

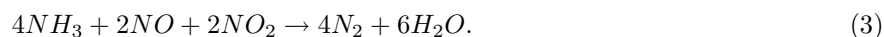
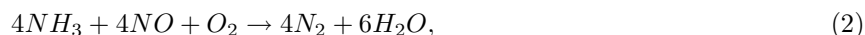
A urea-SCR system plays a significant role not only in the abatement of NO_x but also in the improvement of the economy of the engine (Dieter et al., 2003). It is a well-known technology and can be used for both stationary and mobile applications. The compact urea-SCR can reduce NO_x pollutants by over 70% on the European transient cycle (ETC) and European steady-state cycle (ESC) (Hums et al., 2004). Miller et al. (2000) have reported that the reductions of NO_x and PM with a urea-SCR catalyst are 55.6% and 22.2%, respectively, on the cold US transient cycle, and 70.5% and 25%, respectively, on the hot US transient cycle. According to Wurzenberger and Wanker (2005), the European commission has proclaimed that “Urea-SCR systems are the most promising approaches to comply with Euro IV and Euro V emission standard.”

For an efficient and effective urea-SCR system, it is of utmost importance that the injected urea solution be decomposed completely below 200 °C to avoid the possible production of byproducts such as ammonium nitrate (NH₄NO₃), cyanuric acid ((HNCO)₃), and so on (Nakayama et al., 2006). Moreover, it is also of great concern that the injection system have high precision and be able to respond readily. Thus, it is imperative to develop an SCR system coupled with an engine control module (ECM) using a pulse width modulated (PWM) injector to control the quantity of reductant, and an air assist system to ensure uniform distribution of the reductant in the exhaust stream (Calabrese et al., 2000).

The urea-SCR system is installed in the tailpipe of the engine behind the turbocharger to inject a solution of 32.5% urea (by weight) and water called AdBlue (Dieter et al., 2003). Its working principle is to evaporate and then decompose the urea solution into ammonia (NH₃) (Schar et al., 2003):



Ammonia serves as the reducing agent in the catalyst, and the significant reactions are given as follows:



The aim of this article was to study the impact of a urea-SCR system and thus evaluate its performance for the controlling of regulated gaseous pollutants, such as NO_x, HC, and CO, and the number and size distribution of the particles and carbonyls or carbonyl compounds (CC). Although the current SCR system was primarily designed for the abatement of NO_x pollutants, the objective was extended in this study to unregulated emissions affected by the secondary reactions, which are expected to be promoted with this vanadium-based urea-water SCR system.

Experimental Set-up

Test engine, fuel, and operating conditions

The tests were performed on a turbocharged inter-cooled diesel engine having the specifications listed in Table 1. The engine was fuelled with commercial diesel having the properties and standards given in Table 2, and it was run on an electrical AC dynamometer (Dynas₃ HT350, Schenck) as shown in Figure 1.

The engine torque was measured with the help of a torque flange and read with Automation System STARS Rev. 1.5 software in the control room. The air and fuel flow rates were measured using Sensyflow P (ABB Inc.) and PLU4000 (Pierberg), respectively. In order to measure the coolant and engine oil temperatures, PT-100 sensors were used. For the measurement of exhaust temperature, a thermocouple (k-series) was used.

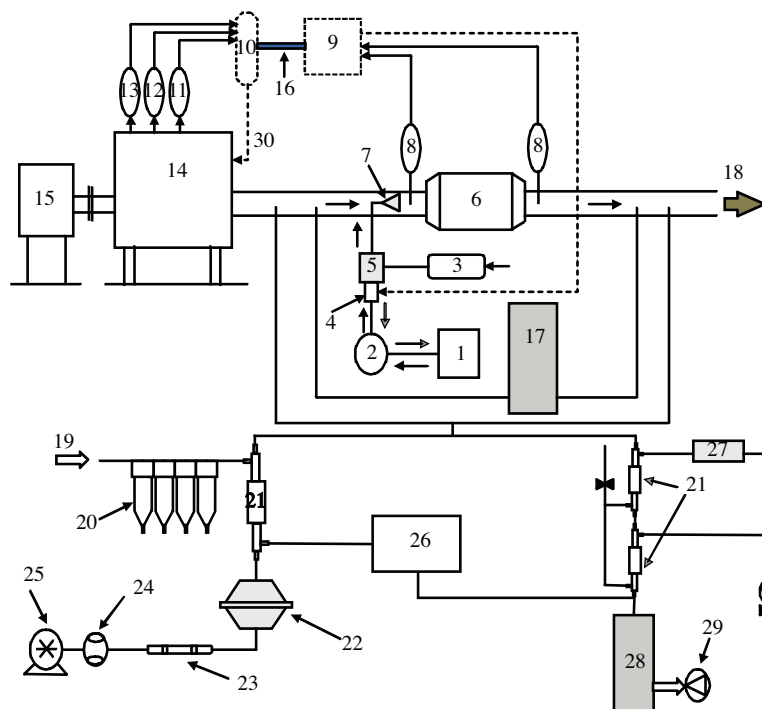


Figure 1. Experimental set-up.

Table 1. Engine specifications.

PARAMETER	FEATURE/SIZE
Engine Type	Diesel, 4-stroke, 4-cylinders, in-line
Air intake system	Inter-cooled, turbocharged
Fuel metering system	High pressure common rail
Valves	2 valves per cylinder
Capacity (cc)	2771
Bore (mm)	93
Stroke (mm)	102
Compression Ratio	18.2:1
Max. Power (kW@r/min)	85@3600
Max. Torque (Nm@r/min)	270@1900

Table 2. Properties of fuels.

PROPERTIES	DIESEL	STANDARD*
Lower heating value (MJ/kg)	42.8	GB/T 384
Viscosity (mm ² /s) at 20 °C	4.0	GB/T 265
Density (kg/m ³)	841	SH/T 0604
Sulfur content (ppm)	350	SH/T 0253-92
Cetane index	52	GB/T 386-91
Oxygen content (%)	0	Element analysis
Hydrogen content (%)	13	SH/T 0656-98
Carbon content (%)	87	SH/T 0656-98

*Chinese standard

The experiments were performed in accordance with the ISO 8178 Type C1 8-mode steady-state cycle (He et al., 2009). According to this cycle, the engine was run at 3600 r/min at 100%, 75%, 50%, and 10% of full load for modes 1, 2, 3, and 4, respectively, and at a speed of 1900 r/min at 100%, 75%, and 50% of full load for modes 5, 6, and 7, respectively; The 8th mode was idle at a speed of 800 r/min.

Urea-SCR system and specifications

The current vanadium-based urea-water SCR system is designated as BiTBlue-P because it was designed and developed at the Beijing Institute of Technology (BIT), Beijing. The SCR system consists mainly of a urea tank, pump, measuring unit, air assistant system, injector, and catalyst, as shown in Figure 1. The ECU of the SCR receives signals of speed, throttle, and catalyst temperature to predict the NO_x emissions, and then gives the control signals to the PWM injector to control the reductant injection time and quantity. The surplus reductant urea goes back to the tank, controlled by the adjustment valve. In the exhaust pipe, the injected urea, in the presence of hot gases, is evaporated, decomposed, and thus hydrolyzed to NH₃.

The pump of the urea SCR, which lets urea exit the tank and enter the measuring unit, is of the type MG204XK/DC24W1, a magnetic gear pump (made by a micropump company in Nanjing, China). The characteristics of the pump are: voltage = DC 24 V; rated pressure = 700 kPa; volume = 20 ~ 1000 mL/min; power = 70 W.

The evaporation, decomposition, and hydrolysis of the reductant urea depend on the type of the nozzle, the size of the injector hole, and the angle of injection. The following are the specifications of the injector: number of holes = 4; diameter of each hole = 0.5 mm; injection angle = 90°.

As for the specifications of the SCR catalyst, all of the catalyzed honeycomb ceramic substrates are of the same type, with a cell density of 62 cell/cm². The geometric dimensions of the catalyst are 190 mm × 320 mm (diameter × length) and 9.07 L volume.

Sampling and measuring of regulated gaseous pollutants and number-size distribution of particles

For the gaseous pollutants, the exhaust was sampled upstream and downstream of the SCR. Regulated gaseous emissions such as HC, CO, and NO_x were measured with a flame ionization detector (FID), non-dispersive infrared analyzer (NDIR), and chemiluminescent detector (CLD), respectively, using the analytical package AMA4000 (Austria).

For the measurement of the number and size distribution of the PM, the exhaust was taken upstream and downstream of the SCR system, as shown in Figure 1. An electrical low pressure impactor (Dekati Ltd., Finland) was used for this purpose. An ELPI is a real-time particle number concentration and size distribution measuring device, consisting mainly of a corona charger, a low pressure cascade impactor, and a multichannel electrometer. It can measure the number-size distribution of particles ranging in size from 7 nm to 10.15 μm in 13 size fractions (ELPI, Dekati Ltd., Finland). Before being introduced to the impactor, the particles are charged by the corona charger of the ELPI and the aerosol is cut off by different size scopes; hence, the electrometer detects their current, which is converted into a particle concentration (He et al., 2008). The exhaust gas taken into the ejector dilutor (Dekati Ltd. Finland) is diluted with dry, particle-free, pressurized air to avoid the overloading of the electrometer. The ejector dilutor, consisting of 2 dilutors, each with a dilution ratio of 8, has an overall dilution ratio of 64. In this study, however, the overall dilution ratio was about 56, depending on the atmospheric conditions. Before sampling the exhaust, the dilutor was calibrated using the 2 concentrations of carbon dioxide (CO_2) that were measured before and after the dilutor, as shown in Figure 1.

Sampling and analysis of carbonyls

The sample was drawn upstream and downstream of the SCR system in 2,4-dinitrophenylhydrazine (DNPH)-coated silica gel cartridges (Supelco, USA) through an ejector-dilutor with a dilution ratio of about 7.65 to dilute the exhaust and control the temperature at 40 $^{\circ}\text{C}$. The exhaust was then passed through a filter to remove the particulates. A battery operated air pump (Air Chek2000, SKC, USA) with a flow rate of 0.5 L/min was employed for a period of 10 min to get the exhaust into cartridges. After the sampling process, the cartridges were sealed and refrigerated at -10 $^{\circ}\text{C}$.

The sampled material trapped in the 2,4-DNPH cartridges was eluted by 3 mL of acetonitrile (Fisher Company, USA) on a solid phase extractor (SPE) (Supelco Inc.), and the filtered solution was taken in a 5 mL volumetric flask to get the constant volume solution. The Environmental Protection Agency (EPA) standard methods TO-11A (USA EPA, 1999) were used to analyze the carbonyls.

An aliquot of 25 μL was analyzed using a high performance liquid chromatographic system (Agilent 1200, USA) equipped with an automatic injector. An Eclipse XDB C18 column (4.6 mm \times 150 mm \times 5 μm) was used to separate the formed carbonyl-DNPH derivatives that were detected by a visible detector at 360 nm. Acetonitrile and water in the ratio of 60% and 40%, respectively (v/v), were used as mobile phases, and the flow rate and temperature gradients were 1.0 mL/min and 25 $^{\circ}\text{C}$, respectively.

After qualitative analysis, compounds were quantified using a commercial standard mixture (Supelco, USA), which contained 14 carbonyl compounds: formaldehyde (FOR), acetaldehyde (ACE), acrolein (ACR), acetone (ATE), propionaldehyde (PRO), crotonaldehyde (CRO), methyl ethyl ketone (MEK), methacrolein (MET), butyraldehyde (BUT), benzaldehyde (BEN), valeraldehyde (VAL), tolualdehyde (TOL), cyclohexanone (CYC), and hexanaldehyde (HEX). For the quantitative analysis, a 5-point external standard method was used to make linear standard curves, and the correlation coefficient was more than 0.999. Due to difficulties in resolving their chromatographic peaks because of their same retention time, acrolein and acetone were quantified together in this study.

Results and Discussion

Regulated gaseous emissions

NO_x Pollutants Figure 2 presents the emissions of NO_x pollutants upstream and downstream of the SCR system and the reduction in these pollutants at various modes of the operating cycle downstream of the SCR. The pollutant conversion or reduction efficiency of the SCR is given by:

$$RE (\%) = (\text{Upstream emissions} - \text{Downstream emission}) \times 100 / \text{Upstream emissions}. \quad (4)$$

It is clear that the RE varied from 11% to 80.5% at various modes, with minimum and maximum reductions at modes 8 and 7, respectively. The NO_x RE of the SCR exhibited a strong correlation with the catalyst temperature and SV for all modes of the cycle. It increased as the catalyst temperature decreased (modes 1-3 and 5-7) with the exception of modes 4 and 8, at which the RE decreased. The SCR showed a maximum RE (more than 50%) at the catalyst temperature ranging from 321-435 °C according to the 8-mode cycle. Catalyst temperatures above or below this range revealed a negative impact on the performance of the SCR system. At mode 8, the SCR exhibited its minimum reduction performance, which was due to the reduction of the catalyst temperature below the lower limit of its optimum range. There is a possibility of production of ammonium nitrate due to the reaction of NO₂ with NH₃ at low temperatures, which can be accumulated on the catalyst at temperatures below 170 °C (its melting point) and thus cover its surface and end the catalytic effect, resulting in a decrease in the NO_x reduction efficiency of the SCR (Saito et al., 2003). During the study, it was seen that the SCR's performance in controlling the NO_x pollutants was stable when the catalyst temperature was above 185 °C and the performance of the SCR was not affected by the ammonium nitrate in this stable range.

Table 3. Catalyst temperature, space velocity, and A/F ratio at various modes of the 8-mode cycle.

MODES	1	2	3	4	5	6	7	8
Catalyst Temperature (° C)	504	435	329	258	418	378	321	140
Space Velocity (10 ³ /h)	44.52	37.94	28.95	22.77	35.62	32.49	27.63	11.94
A/F Ratio	24.5	30.8	37.6	48.5	23.3	29.2	35.4	85.4

Space velocity is an important parameter of the urea-SCR system and plays a significant role in the RE of the SCR. It is well known that gas SV is defined as the volume flow rate of the engine exhaust per unit volume of the catalyst. Mathematically, this is given by:

$$SV = Q_v / V_c \quad (5)$$

where Q_v and V_c are the volume flow rate and catalyst volume, respectively. It can be seen from Figure 2 and Table 3 that for load modes of each speed (i.e. 3600 rpm and 1900 rpm), the reduction efficiency of NO_x increased with the decrease in SV, with the exception of mode 4 at 3600 rpm. The RE became 42% at mode 4, which means that the catalyst can maintain a high RE only in a certain range of SV. Below or above this range, the SCR performance is adversely affected owing to its catalyst sensitivity to SV.

As presented in Figure 2, upstream and downstream NO_x pollutants also reflected a correlation with engine load, as they decreased with the decrease in engine load (modes 1-4 and 5-7). This decrease in NO_x is attributed to the decrease in combustion temperature at lower loads, because combustion temperature plays a critical role in the formation of nitric oxide (NO) and in the oxidation of NO₂ (Heywood, 1988).

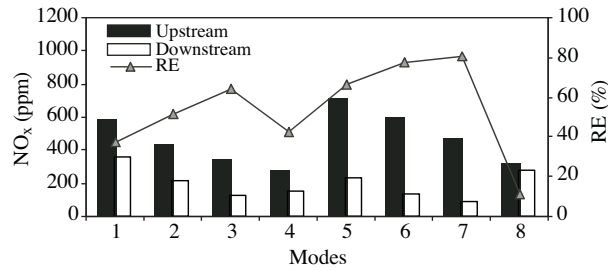


Figure 2. NO_x emissions and the impact of urea-SCR on their reduction.

HC Pollutants Figure 3 shows the upstream and downstream HC emissions and their reduction with the use of the urea-SCR system. The RE of the SCR varied from 38.7% to 71.1% at various modes of the cycle. This finding is in agreement with those of previous studies that urea-SCR systems reduce or convert HC pollutants (Gekas et al., 2002; Scarnegie et al., 2003;. The higher HC reduction performance exhibited by the SCR may be due to the tendency of the catalyst to be more receptive to hydrocarbon storage in its porous walls.

It is evident from Figure 3 that HC emissions were higher at mode 1 (full load) than at mode 2 or mode 3, which first decreased and then tended to increase with the decrease in load at 3600 rpm. In the case of 1900 rpm, HC emissions increased with the decrease in load. These trends were more uniform for upstream emissions. However, downstream HC emissions did not exhibit a clear trend.

Higher HC emissions at lower loads are attributed to the lean mixture or higher value of the excess air ratio (λ), but higher HC emissions at mode 1 are attributed to the relatively rich mixture area developed in the combustion chamber. First the oxygen concentration may be dominant and HC emissions may decrease at mode 2, but then cooling may be dominant and HC emissions may increase with the decrease in load. The unreasonable trend of HC emissions downstream of the SCR is due to the varying oxidation process across the catalyst for different modes depending on various parameters of the SCR system.

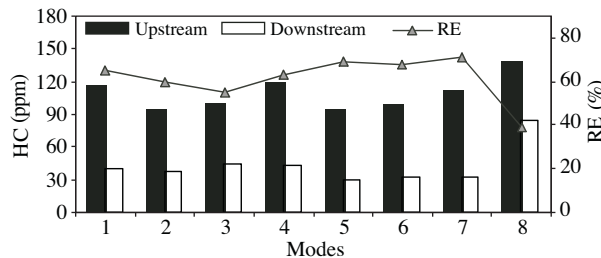


Figure 3. HC emissions and the impact of urea-SCR on their reduction.

CO Pollutants As presented in Figure 4, the downstream emissions of CO were higher compared to the upstream emissions, and hence the RE of the SCR was negative for all 8 modes of the cycle, ranging from -1.5% to -72%. This finding that urea-SCR increased CO emissions is similar to those of previous studies (Miller et al., 2000; Gekas et al., 2002; Scarnegie et al., 2003; Acharya et al., 2006;. The negative RE of the SCR in the case of CO is ascribed to some of the hydrocarbons that form CO instead of CO₂ during their oxidation (Gekas et al., 2002), even though the majority of them oxidize in the presence of SCR as shown in Figure 3. Furthermore, the reductant urea may also produce CO because each urea molecule carries a carbonyl group (–C = O –) (Acharya et al., 2006).

It is obvious from Figure 4 that upstream and downstream CO emissions tended to increase with the decrease in load (modes 1-4 and 5-7). This increase in CO emissions is attributed to the lean mixture area developed in

the cylinder at lower loads. Basically, the rate of CO formation is a function of the unburned gaseous fuel and the mixture temperature in the combustion chamber of the cylinder, which control the rate of oxidation and the decomposition of the fuel (Kouremenos et al., 1999).

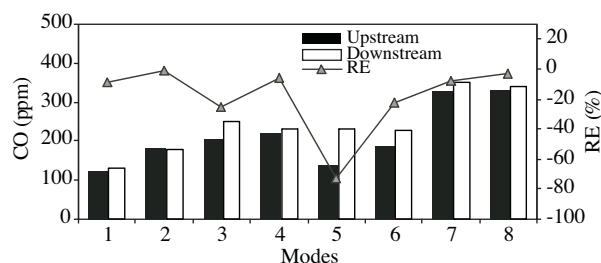


Figure 4. CO emissions and the impact of urea-SCR on their reduction.

Number concentrations and size distributions of particles

Diesel exhaust contains particles of diameters 5-50 nm, 50-1000 nm, and more than 2.5 μm in nuclei, accumulation, and coarse modes, respectively (Wong et al., 2003). Particles are made up of metals, solid carbonaceous materials, and absorbed constituents such as sulphates, volatile organic compounds (VOCs), and water (Zervas et al., 2005 and references therein). The nanoparticles have a higher probability of being inhaled and deposited in the respiratory tract and the alveolar region by diffusion, and thus may cause inflammation, damage to lungs, and respiratory diseases (Donaldson et al., 1998). Therefore, the measurement of particle number instead of mass is proposed for future emission legislation (Zervas and Pascal, 2006).

Figure 5 displays the upstream and downstream SCR number-concentrations and size-distributions of the particles at different modes of the 8-mode cycle. It is clear that number-concentrations of the particles with aerodynamic diameter 7-57 nm (in nuclei mode) were in abundance both upstream and downstream of the SCR for all the modes of the cycle. The higher number of these nanoparticles may be due to their rapid nucleation in the dilutor. According to Vaaraslahti et al. (2004), nucleation mode particles are composed of VOCs and sulfur compounds, which nucleate during the dilution process as the diesel exhaust comes out the tail pipe.

However, the nanoparticles as well as the total particle numbers were fewer downstream of the SCR than upstream. Moreover, the number concentration peaks were greatly reduced with the SCR for all modes of the cycle. The most significant reduction in the number concentrations of the particles occurred in the size range of 7-57 nm. The downstream SCR nanoparticle and total particles numbers were 24% to 55% and 17% to 50% lower than the corresponding upstream nanoparticle and total particle numbers, respectively, for all 8 modes of the cycle. The decrease in particle number concentrations was less for the size range of 57-255 nm. Particles larger than 255 nm showed haphazard trends in their number concentrations across the SCR. At some modes, their downstream concentrations decreased, but at some others they increased. This may be due to the performance limit of the SCR catalyst, which means that it cannot decrease the large solid particles contributing the most to the insoluble particulate mass (Gekas et al., 2002). Even though the SCR did not exhibit stable performance in the reduction of particle numbers of diameters more than 255 nm, its impact on the total particle numbers, and particularly on nanoparticles, was remarkable. This reduction in total particle numbers and the shifting of their number-size distributions from smaller sizes to larger sizes is attributed to the oxidation of HC, constituting a part of the PM, and hence to the increase in the hydrocarbon RE of the SCR, as shown in Figure 3. Moreover, it has also been reported that SCR systems have the potential to reduce the

volatile fraction in a manner similar to that of oxidation catalyst (OC), thus affecting the size distribution in a way similar to that of OC (Vaaraslahti et al., 2004).

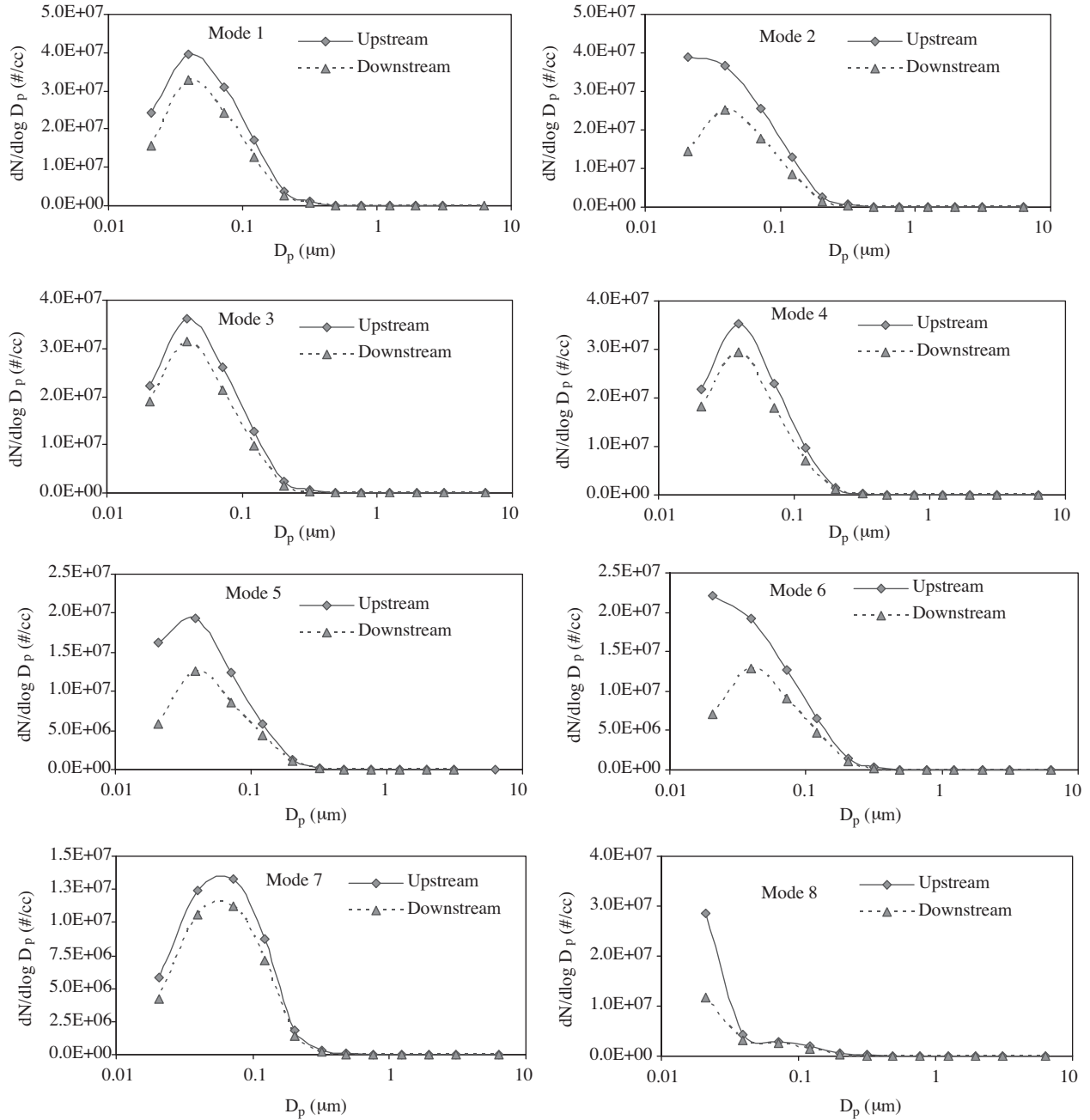


Figure 5. Impact of urea-SCR on number-size distribution of particles at various modes.

Carbonyl emissions

Carbonyls are toxic air contaminants that play a decisive role in tropospheric chemistry. They are important precursors of ozone, free radicals such as HO_x , and peroxyacyl nitrates (PAN) (Guariero et al., 2008 and

references therein). This group of pollutants is ranked after NO_x , one of the most powerful agents notorious for smog formation (Haupt et al., 2004).

Figure 6 presents the carbonyl emissions upstream and downstream of the SCR together with the RE of the SCR. The vanadium-based urea-water SCR showed a significant impact on the reduction of carbonyls at various steady-modes, and its RE reached 55.3% at mode 7. However, at mode 8 the SCR system exhibited reluctance to conversion or reduction of carbonyls, thus revealing a negative RE. The reduction in carbonyl emissions with the SCR is attributed to the oxidation of HC pollutants across the SCR, because carbonyls are partially oxidized species of HC pollutants, which increase with the increase in unburned HC (Wagner and Wyszynski, 1996; Warner et al., 2003;. A similar trend was also observed in this study, in general and at modes 1, 2, 4, and 7 in particular.

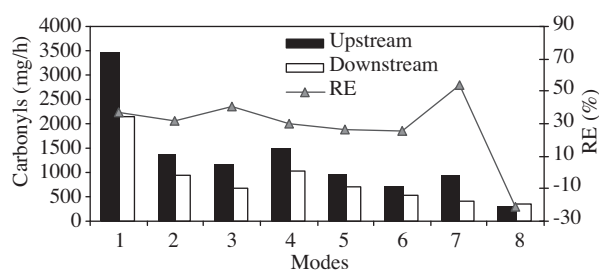


Figure 6. Impact of urea-SCR on carbonyl emissions.

Formaldehyde, acetaldehyde, acrolein and acetone, and propionaldehyde have been separately discussed further in Figure 7 for 2 main reasons. First, these compounds contribute the most to the total carbonyl emissions from a diesel engine. Turrio-Baldassarri et al. (2004) studied diesel oil and a mixture of this diesel with 20% biodiesel (by volume) and reported that 90% of the carbonyls from a diesel engine consisted of formaldehyde, acetaldehyde, acrolein, and propionaldehyde. Second, formaldehyde and acetaldehyde have been pointed out as probable carcinogens by the World Health Organization (WHO), the National Institute for Occupational Safety and Health (NIOSH), and the European Union (EU), while the EPA has declared acrolein as a possible human carcinogen (Nord and Haupt, 2005).

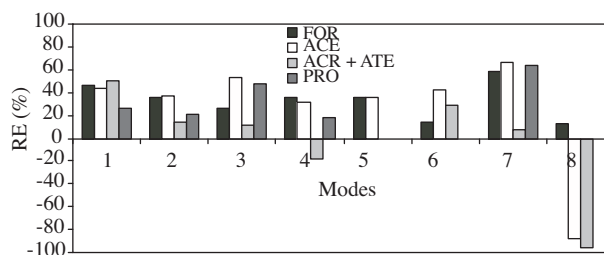


Figure 7. Impact of urea-SCR on some selected carbonyls.

Formaldehydes, which are the result of incomplete combustion and low cylinder temperature (Cardone et al., 2002), showed significant reduction with the SCR. This reduction reached about 58% at mode 7, as shown in Figure 7. Acetaldehyde and propionaldehyde also exhibited their maximum reductions at various modes, which reached 67% and 64%, respectively, at mode 7. However, acrolein and acetone displayed their maximum reduction of about 50% at mode 1. The maximum RE of the SCR for formaldehyde, acetaldehyde,

and propionaldehyde at mode 7 is again attributed to the maximum reduction of HC (about 71%) at this mode of the cycle.

Conclusions

A vanadium-based urea-water SCR system was evaluated on the basis of its potential to reduce the exhaust emissions from the tailpipe of a diesel engine. Both NO_x and HC pollutants were substantially reduced, while the maximum RE was up to 80.5% and 71.1%, respectively. The RE of the SCR was greatly influenced by the catalyst temperature and SV, and NO_x increased with the decrease in SV within the load modes of each cyclic speed. The SCR exhibited a maximum RE of 80.5% for NO_x emissions at 321 °C, while the RE was more than 50% when the operation window was at 321–435 °C. Both upstream and downstream NO_x were decreased, whereas HC and CO emissions increased with the decrease in engine load. The SCR system exhibited a negative RE for CO emissions at all cyclic modes.

The number-concentrations of particles with an aerodynamic diameter of 7–57 nm were in abundance both upstream and downstream of the SCR. However, nanoparticles, concentration peaks, and total particle numbers were substantially reduced with the SCR system. The decrease in particle number concentrations was less for the size range of 57–255 nm, while particles larger than 255 nm revealed haphazard trends in their number concentrations. The number-size distribution of particles shifted from smaller to larger sizes with the urea-SCR system.

Carbonyl emissions were greatly reduced in the presence of the SCR system, while the maximum RE was 55.3%. Some important carbonyl species like formaldehyde, acetaldehyde, acrolein and acetone, and propionaldehyde revealed substantial reductions of up to 58%, 67%, 50%, and 64%, respectively.

Acknowledgement

The authors gratefully acknowledge the support of the Laboratory of Auto Performance and Emission Test, School of Mechanical Engineering, Beijing Institute of Technology (BIT), Beijing, P.R. China. The authors would like to thank Dr. TAN Jianwei for his help in conducting the experiments. This study was financially supported by the National Natural Science Foundation (NNSF) under Project No. 50876013.

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