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Research on Urea Jet Pump Performance Characteristics using the Optimized NO_x Removal Equipment in Diesel Engine

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ABSTRACT

There are many factors that affect the efficiency of NO_x conversion in the diesel engine SCR (selective catalytic reduction) post-processing system. In this study, we researched the factors affecting the efficiency of NO_x conversion by engine bench testing. The SCR system was applied to the Weichai WD615 engine exhaust. First, the system used DOC (Diesel Oxidation Catalyst)/DPF (Diesel Particulate Filter) of which DOC is a noble metal-containing filter, it lets the filter passes through converting nitrogen monoxide (NO) to nitrogen dioxide (NO_2) for passive regenerations and to provide high hydrocarbon (HC) oxidation activity for active DPF regenerations, the DPF is a wall-flow filter used to trap the remaining soot that the DOC can not oxidize. The combined catalytic oxidation device improved the original SCR deNOx system, which we developed. The new catalytic oxidation apparatus has a simple structure and fundamentally solves the clogging problem of the SCR method and the defects led by the unstable gaseous ammonia generation. Secondly, we studied the influence of an increased urea injection on the conversion efficiency of NO_x and the secondary pollution of NH_3 at different speeds and torques of the engine. It was found that at the maximum removal rate, the downstream NO_x concentration was only 1 ppm. The NO_x conversion efficiency can reach 79.10% or more—even 99.90%. Finally, we used the KDS and the BOSCH urea injection pumps to analyze the effect of different pumps on the conversion efficiency of NO_x. Hence, the matching diesel engine urea SCR post-processing system can reduce the emission concentration and pollution. There was little difference between the two pumps under most of the working conditions, although KDS was a little better than BOSCH under some individual conditions.

Keywords: Diesel engine exhaust; Optimized catalytic device; SCR system; Urea injection; Conversion efficiency.

INTRODUCTION

Research Background

Due to its high compression ratio and fuel distillation operation, diesel engines have inherent high thermal efficiency, high dynamic performance, and economic fuel efficiency (Beeck *et al.*, 2013).

While high compression ratio achieves the high-temperature ignition required, and the resulting high expansion ratio releases less heat in the exhaust emissions of the engine. Diesel engines become the trend of automotive industry nowadays (Borman and Ragland, 1998). Because there is a huge potential to improve it in the emission performance, diesel engines have been widely used in the world (Agarwa *et al*, 2017). However, due to the diesel engine itself and the use of fuel containing amount of oil substances with high-ignition point, the gasoline-diesel can't be completely burned in the cylinder (Aboughaly, 2016). There are a large number of toxic and harmful pollutants in the exhaust, including CO, CO_2, NO_x, CH, particulate matter (PM) and so on, even oil and asphalt which is unbleached microfine drops (Tutak *et al.*, 2015). Among these exhaust, NO_x, CH, CO and other diesel engine combustion are the main pollutants in the environment, they cause photochemical smog, acid rain, and other hazards (Skalska *et al.*, 2010). After the human inhaled these pollutants, these pollutants can impede the transmission of the nervous system, it makes hemoglobin mutation damaging on the eyes, respiratory and lung function (Asante-Duah, 2017). At the same time, after ultraviolet radiation from the strong sunlight, CH and NO_x occurred complex photochemical reactions, resulting in a new pollutant photochemical smog (Seinfeld and Pandis, 2016), leading to bronchitis, coronary heart disease and heart failure and other events will be significantly increased (Alcamo and Olesen, 2012). The standard of emissions limits of nitrogen oxides,

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particulate matter, carbon monoxide and hydrocarbons in diesel engine exhaust are becoming more stringent (Wattrus *et al.*, 2016). It has promoted the development of efficient post-processing system of diesel engine (Johnson, 2009), exhaust gas purification technology has become the focus of research at home and abroad. Experts believe that it becomes difficult to meet the requirements of emission regulations through the combustion optimization and other internal control measures (Eckerle *et al.*, 2017). And the traditional treatment technology model has high investment and operating costs, high catalytic activity, low capacity and poor stability are still a common problem of catalyst (Johnson, 2011; Kalghatgi, 2015). At the beginning of 2010, most of the new medium and heavy diesel vehicles on major international markets, such as the US, Europe, and Japan, relied on urea-based SCR technology to meet the most stringent NO_x emission regulations (Johnson, 2012). In general, the advantages of SCR are the high NO_x reduction efficiency, the durability performance, the wide performance window, the reasonable cost and the available infrastructure, which are satisfactory (Zhan *et al.*, 2012). With EPA 2015 stringent management of large diesel engines for locomotives, ships and fixed generators, due to the proven performance of urea SCRs on highway and off-highway (Liu *et al.*, 2017), the demand for NO_x reduction through urea SCR catalysts is increasing (Ballinger *et al.*, 2009; Theis, 2009; Beeck *et al.*, 2013; He *et al.*, 2017).

Research Purpose

Based on the SCR deNOx technology, the experimental platform was established with Weichai WD615 diesel engine. Improving the conventional DOC + DPF + SCR model for diesel engine reprocessing technology (Hsieh *et al.*, 2011), it used catalytic oxidation granular bed system prepared by the rare earth molecular sieve which can oxidize CO, CH and also eliminate the fine PM particles to replace the original DOC + DPF mode. The device was set at the exhaust outlet of the diesel engine. After the diesel engine exhaust passed through the device, the CO, NO_x, CH, PM, most of the fine carbonized particles, the unburned micro-droplets of oil and other similar substances in the exhaust could be trapped by the pretreatment device, so the diesel engine exhaust after passing through the pretreatment device was much cleaner in the SCR catalytic reduction system.

At the same time, the granular bed system can be replaced the molecular sieve at any time in the off-line mode, and realized the regeneration of the molecular sieve by the in-situ regeneration technology. It achieved the low-cost recycling and long-term use to improve the NO_x removal efficiency of the SCR system. It solved the problem that the removal efficiency was pulled down by the failure of the catalyst and the irreplaceability which caused the accumulation of pollutants on the catalyst surface to form an isolation layer. And it studied the effect of the modified catalytic device on the NO_x, CH and CO emissions in diesel engine exhaust. The technical route can not only solve the problem of pollutant emission reduction technically but also can definitely be used in the practical application, in which the simplicity of modification, economic acceptability, and maintenance convenience are the key points.

Secondly, it is very important for the improvement of denitration efficiency to control the urea injection system reasonably in SCR system. The urea injection system is the core part of the SCR system denitrification function. Using non-standard vehicle urea solution will lead to serious impacts on the entire post-treatment system, such as urea nozzle clogging, urea pump crystallization (Maunula, 2013). At the same time, in order to improve the efficiency of NO_x conversion, it needs to control the amount of urea injection to prevent excessive ammonia spray, which will lead to the “ammonia escape” (Farshchi *et al.*, 2001), causing poisoning. Urea deposits can cause backpressure, engine power loss, and material deterioration due to incomplete evaporation of the urea solution (Koebel *et al.*, 1996). The catalyst poisoning is due to the reaction between ammonia and sulfurs those results in solid chemical deposition on the surface of the catalyst, such as ammonium bisulfate. The urea pump is the power element of the urea injection system. When the diesel engine is working properly, the urea pump draws the urea solution from the urea tank. If the diesel engine stop, the urea pump returns the urea in the pipe and the nozzle to the urea tank (Sun *et al.*, 2012). When urea spray resistance increases, the life of urea pump will reduce, also the maintenance and repair costs will increase significantly. Emissions can’t meet the standard, which will cause the phenomenon of engine weakness, it affects transport efficiency. Therefore, in order to further acknowledge the effect of different urea pumps on the denitrification efficiency of SCR system, it chose two different urea pumps, i.e., KDS pumps and Bosch pumps, to compare their performance under different urea injection.

METHODS AND MATERIALS

Laboratory Equipment, Instruments, and Reagents

Test Instrument and Equipment

The test instrumentation is shown in Table 1.

It used the Weichai WD615 engine in this experiment, with the maximum output power rating of 266 kW, the rated speed of 2200 rpm, the maximum torque of 1460 N·m at 1400–1600 rpm. The main technical specifications of Weichai WD615 engine are as the following Table 2.

It used D480 hydraulic dynamometer to detect the power of diesel engines in this experiment. The hydraulic dynamometer with a simple structure is to operate easily and has good regulation, smooth work and so on, it can be used widely. Torque measurement is indicated by scale pointer. The measuring accuracy of torque is ± 5% F.S. The measuring accuracy of motor speed is ± 1 p. It is loaded by adjusting the flow of inlet valve.

Dual-use petrol and diesel car vehicle exhaust gas analyzer measures the exhaust emissions when the vehicle is at idle, as well as transient measurement of diesel fuel emissions under the situation. It mainly measures the HC, CO, CO_2 and NO concentration of the exhaust emissions from the vehicles exhaust emissions. It shows both opacity and

Table 1. Test instrumentation and equipment.

Number	Device	Model	Manufacturers
1	Dynamometer	D480	Qidong Huayang Power Test Equipment Co., LTD
2	SCR electronic control system	One set	Nantong Enpu Environmental Technology Co., LTD
4	Fuel consumption meter	FC2210	Xiangyi Co., LTD
5	Dual-use petrol and diesel car vehicle exhaust gas analyzer	SV-YQCH Model	Tianjin Shengwei Development of Sciebnce Co., Ltd.
7	Diesel engine	WD 615	Weichai Power Co., Ltd
8	DOC+DPF combined granular bed post-processing system	SMKQ-1	Suzhou Shuimukangqiao Environmental Engineering Technology Co., LTD
10	Calibration gas	Mixture gas	Shanghai Shenkai gas Technology Co., Ltd

Table 2. The main technical specifications of diesel engines for testing.

Engine model	Unit	WD 615
Engine type	-	Water-cooled, inline, four-stroke, dry cylinder sets, direct injection, pressurized, pressurized in the cold
Bore	mm	126
stroke	mm	130
Oil supply		High pressure common rail
Oil Pressure	bar	1600
Displacement	L	9.726
Calibration power/calibration speed	kW (r min^{-1})	240/2100
Maximum torque/speed	Nm (r min^{-1})	1428/(2300)
The highest empty car	r min^{-1}	2300
Idle speed	r min^{-1}	600 ± 50
The minimum fuel consumption rate of external characteristics	g $(kW.h)^{-1}$	190.8
Engine oil pressure	MPa	Rated condition: 0.35–0.55; Idle speed: 0.10–0.25
Engine oil temperature	°C	Rated condition:80–95; Idle speed: 75–100
Diesel oil temperature	°C	38 ± 3
Air temperature after the cold intake	°C	50 ± 5
Diesel engine water temperature	°C	80–93
Turbine rear exhaust temperature	°C	≤ 600
Exhaust back pressure	kPa	≤ 15
The highest burst pressure	MPa	16

light absorption coefficient readings; with free acceleration experiment and transient measurement functions, processing of test data and display of measurement results. Its measuring range for each substance is:

It shows both opacity and light-absorbing coefficient these two readings: It has the function of free acceleration experiment and transient measurement. It deals with the test data and displays measurement results. Its measurement range of each substance is: CO: 0–10%; HC: 0–10000 ppm; NO: 0–5000 ppm; N: 0–99.9%. Its motor speed is 100–20000 rpm.

The measurement and control system (SCR electronic control system) consists of four parts: sensing detection section—perceived information (sensing technology, detection technology); information processing section—processing information (artificial intelligence, pattern recognition); information transmission section—transmission of information (wired, wireless communication and network technology); information control section—control information (modern control technology), the measurement process through the sensor to obtain the measured physical parameters of the electrical signal or control the process of state information, through the serial or parallel port to receive digital information, the use of computerized system can easily achieve the control program. Fuel consumption instrument mainly take dynamic monitoring and fault analysis on the diesel engine ignition, fuel, power, charging and so on.

FC2210 Advanced Fuel Consumption Measurement Device has the integrated design with a complete set of fuel consumption measurement and display instrument. It can independently measure the engine fuel consumption. The display instrument of FC2210 Advanced Fuel Consumption Measurement Device adopts the given time weight measurement method. It requires the ambient temperature is 0–40°C; relative humidity does not exceed 85% RH. The measurement ranges from 0 kg to 40 kg, a total of 10 specifications; measurement accuracy: 0.4% F.S.

Measurement time can be set by keyboard with the range 1 second to 200 seconds. Measurement result is shown as the form of 4-bit floating-point numbers in kg h^{-1}. By a normally closed two-way solenoid valve, the fuel filling process is controlled. When the solenoid valve is in open condition, fuel tank directly supplies fuel to engine oil while supplying to the fuel cup as well. When the fuel surface of fuel cup reaches upper limit, the solenoid valve is closed and stopped the fuel tank to supply fuel to engine. At the same time, the required fuel for engine is supplied by fuel cup.

Through the ion-exchange modification, dealumination modification, heteroatom isomorphous substitution modification, pore and surface modification, modified molecular sieve has been designed structurally and researched how to shape modeling. It has mastered the core technology of mesoporous molecular sieve on adsorption, catalysis, separation, and chemical assembly preparation. In addition to dealing with the selective adsorption of CO, NO_x, HC, and PM in engine exhaust gas, the molecular sieve has the characteristics of large saturated adsorption capacity, fast desorption speed, and long service life, it has been successfully applied on VOCs, H_2O, HC, PM removal.

Rare earth molecular sieve particles are composed of rare earth zeolite particle bed. Modular rare earth molecular sieve particles are mounted inside a stainless steel plate frame with stainless steel mesh filters on both sides. It consists of multiple rare earth molecular sieve modules with multi-layer parallel in the device. When the diesel outlets exhaust the gas after the urea injection zone, it directly entered the granular rare earth molecular sieve granular bed. When the exhaust gas went through the particle bed composed of dense particles, it intercepts and retains various types of solid particles and micro-droplet substances in the exhaust gas.

At the same time as the particle surface contains a higher concentration of lanthanum, cerium and other rare earth elements, these lanthanum, cerium, and other rare earth elements are also good selective reduction of nitrogen oxides catalyst. Specifically, when carrying out molecular sieve particle coating, a catalyst slurry is first formed by using a salt containing one or more elements of zirconium, cerium or lanthanum, and then coated on the adsorbed particles after nonionic surface-active treatment, and finally dried and calcined to obtain the molecular sieve particles, the upper amount of the catalyst slurry needs to reach 10–25% of the weight of the adsorbed particles. Nitrogen oxides in diesel exhaust can be removed for the first time, thus it can improve the denitrification efficiency of the entire purification device.

The particulate filter device is an oxidized particulate filter device1, it is used to remove CO, HC, ultra-fine carbon particles and large-sized particles in the flue gas. In addition, the catalytic oxidation/reduction device includes an SCR Reactor 2 for removing nitrogen oxides, carbon monoxide and hydrocarbons. In particular, the oxidized particulate filter device1 is a bed of rare earth molecular sieve particles coated with a rare earth element such as lanthanum cerium. The particle size of the molecular sieve particles can be adjusted as needed. The average size of the molecular sieve particles is 8–10 mm. The working temperature of the oxidized particulate matter filter device 1 is 290–360°C.

In general, catalytic particle bed filtration device can occur the catalytic oxidation reaction only maintaining the temperature above 280°C. The catalytic particulate filtering device is the oxidative type. The catalytic oxidation reaction in a catalytic particulate filter device is an exothermic reaction. As long as the amount of flue gas can be controlled to some extent, the temperature of the flue gas can be elevated to about 350°C, thus it not only ensure the catalytic oxidation demand in the catalytic granular bed filtration device but also can satisfy the requirements of the next stage demand for the reaction temperature for the reduction reaction in the SCR reactor 2. In this way, there is no need to add additional heating units, it saves investment and reduces equipment size

While the high-temperature flue gas filtered by the catalytic granular bed filtration device enters into the next-stage SCR reactor 2, a reduction reaction occurs. Large-sized particles in the high-temperature flue gas are intercepted in the catalytic granular bed filtration device, thus it can ensure that the sufficient reduction reaction occurs in the reactor 2, and in addition, the large-sized particles intercepted in the catalytic bed filtration device can be removed with a reverse air.

Test diesel engine bench based on the drawings is shown in Fig. 1.

Reagents

Standard calibration gas, urea, water, GBIV diesel oil, engine oil.

Measurement Methods

Diesel engine exhaust composition was closely linked with working conditions. It adopted D480 hydraulic dynamometer provided by Qidong Huayang Test Equipment Co. Ltd. to measure the working condition of the diesel engine. Also, the exhaust composition was recorded by SV-YQ gasoline/diesel dual-use exhausts gas analyzer provided by Tianjin Shengwei Technology Development Co. It can measure CO, HC, CO_2, NO_x and other emission components in the exhaust gas. Non-dispersive Infrared Analyzer (NDIR) measurement was used for the exhaust emissions of CO, HC, CO_2. Electrochemical cell sensor is for measurement of the concentration of NO_x (Wang *et al.*, 2000). When infrared light passes through the gas to be measured, infrared light of a particular wavelength is absorbed by these gas molecules, and the relationship is obeying the Lambert-beer absorption law. In operation, the sensor emits infrared light according to the set modulation frequency. Infrared light is incident on the measuring chamber through the material. The measured gas is passed into the measuring chamber by the sampling pump. The gas absorbs the infrared light of specific wavelength. Infrared light is detected by the infrared detector, and the output AC signal, and then through a high-precision amplification rectifier circuit, get measured

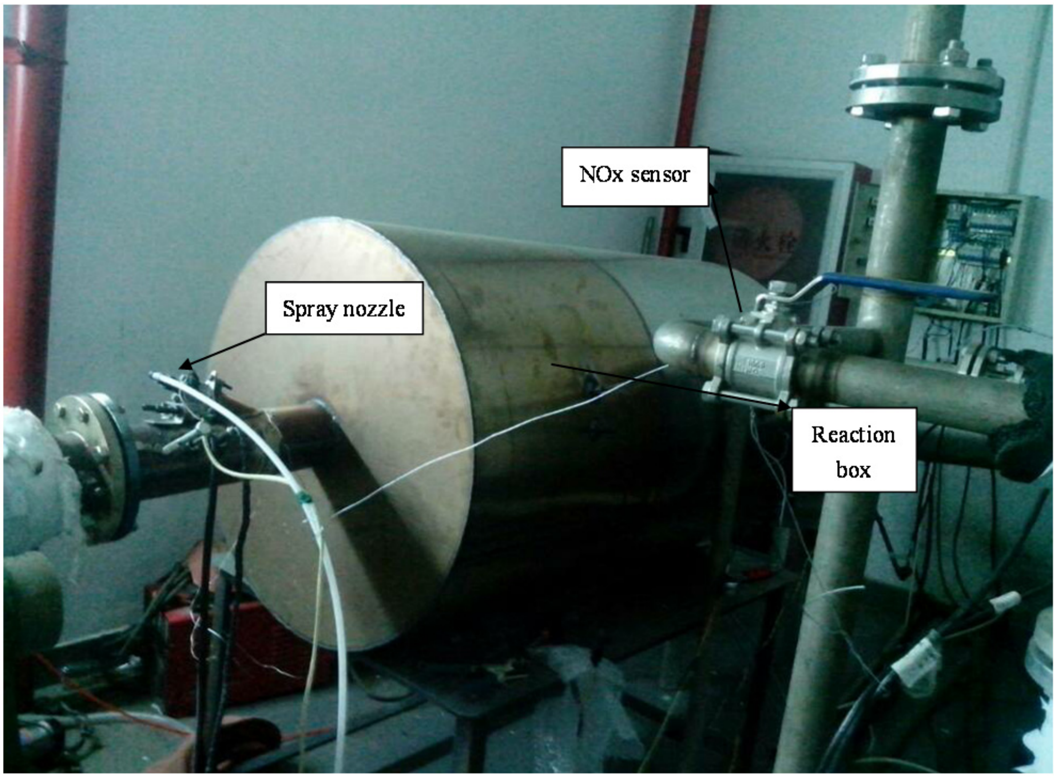

Fig. 1. Diesel engine bench.

gas concentrations corresponding to the DC signal into the measurement and control system. Infrared sensor with a temperature sensor can show the magnitude of gas concentration through the control system, and digital filtering, linear interpolation and temperature compensation software (Werle *et al.*, 2002).

In accordance with the "GB17691-2005 limits and measurement methods for exhaust pollutants from compression ignition and gas fuelled positive-ignition engines of vehicles", steady-state emission European steady state cycle (ESC) 13 operating point was performed by the use of WD615 diesel engine. And the national diesel engine external characteristic curve experiment IV is completed. The steady-state test ESC13 operating conditions include:

① Idle speed, one case

② When the speed is A, the load is 25%, 50%, 75%, 100% and so on 4 cases

③ When the speed is B, the load is 25%, 50%, 75%, 100% and so on 4 cases.

④ When the speed is C, the load is 25%, 50%, 75%, 100% and so on 4 cases.

The speed A, B, and C are calculated from the external characteristics of the diesel engine. The speed is A = Nlo + 25%(Nhl – Nlo), B = Nlo + 50%(Nhl – Nlo), C = Nlo + 75%(Nhl – Nlo), where Nlo is the external characteristics of the minimum speed experiment, Nhl is the external test the maximum speed.

Based on the 13 working conditions, it took the WD615 IV diesel engine as the experimental object, with the SV-YQCH exhaust gas analyzer, D480 hydraulic dynamometer. First, it completed the experiment of comparing the different NO_x concentration between the traditional machine and the optimized catalytic device under the different conditions and recorded data.

Then, it recorded the data of the NO_x conversion efficiency based on the optimized catalytic oxidation bed system, equipped with SCR post-processing system. The parameters measured by various temperature and pressure sensors included speed, torque, power, fuel consumption, fuel temperature, oil temperature and pressure, exhaust temperature and pressure, inlet temperature and pressure, inlet and outlet temperature of the cooling water, SCR system upstream and downstream NO_x concentration and so on.

Based on the improved catalytic device, the effect of urea injection and NO_x concentration conversion experiment was carried out.

RESULTS AND ANALYSIS

Results of NO_x *Emissions Research and Analysis*

Analysis of Urea Injection Efficiency and NO_x *Conversion Efficiency Based on Improved Equipment*

Due to limited time and conditions, this test has selected the work conditions 3, 4, 5, 6, 9 together with the idle speed from the total 13 working conditions. So, a total of 6 points are set as the test points, which represented the engine running performances. They were typical emission points, of which each representative operating point is for urea injection and NO_x conversion efficiency analysis based on a modified device. The test results were respectively shown in Figs. 2–8.

Under each condition, the downstream NO_x concentration

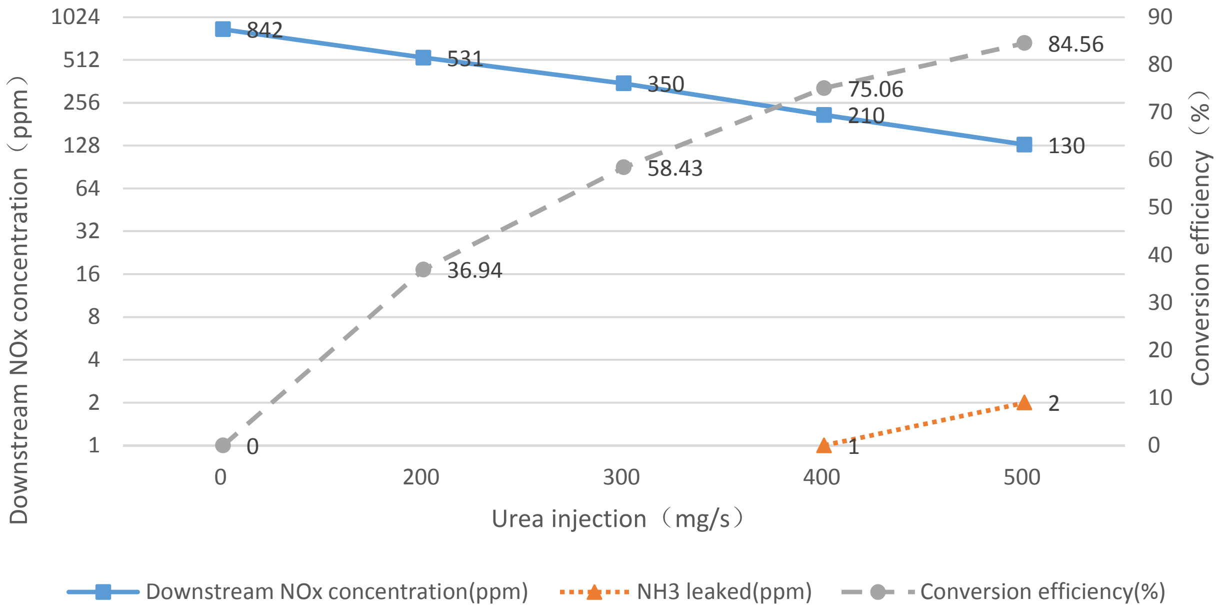

Fig. 2. The relationship between urea injection and NO_x conversion efficiency under Case 3.

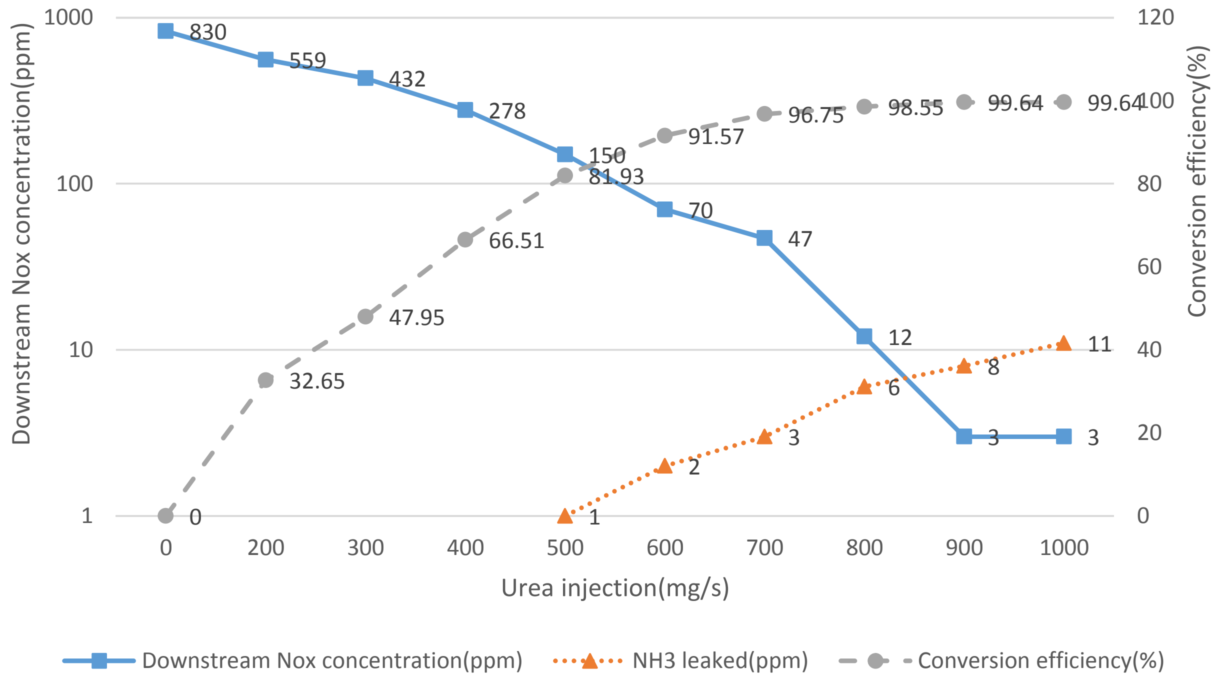

Fig. 3. The relationship between urea injection and NO_x conversion efficiency under Case 4.

decreased with the increase of urea injection, and the conversion efficiency increased. At the same time, the leakage amount of NH3 was beginning to appear while the urea increased to a certain value, and grew. It showed in the condition 3, 4, 5, 6, 11, 13 of BOSCH. Bosch 2.2 Urea system can be divided into the working process of self-test standby, pre-injection pressure, injection, inverted pumping emptied four stages. In the first stage, the pump motor runs, the urea solution in the urea tank is sucked into the pump through the liquid inlet, and the urea solution passes through the liquid pipe under the motor to reach the diaphragm of the urea pump motor (Note: the urea membrane pump = urea pump motor + diaphragm structure), with the hydraulic diaphragm reciprocating motion generated by the subsequent pipeline is pushed to the filter. In the second price segment, after filtering in the filter cavity, all the way urea solution enters the urea injection pipeline through the pipeline between the outlet (the direction of urea nozzle) and the filter cavity through the outlet, the other urea solution flows through the urea pressure sensor to the return port, and then back to the urea tank through the return port pipe. Then, in the return valve (reverse solenoid valve) pressure limiting role, the pump will continue to rise in urea pressure, when more than 8 bar urea pressure can be maintained at between 8–9 bar (pump pressure sensor will collect pressure signal), and enter the waiting for urea injection or direct injection state. At the beginning of pressure build-up, the nozzle connected to the injection pipe will also be opened to discharge the air in the injection pipe so that the urea solution can fill the injection pipe.

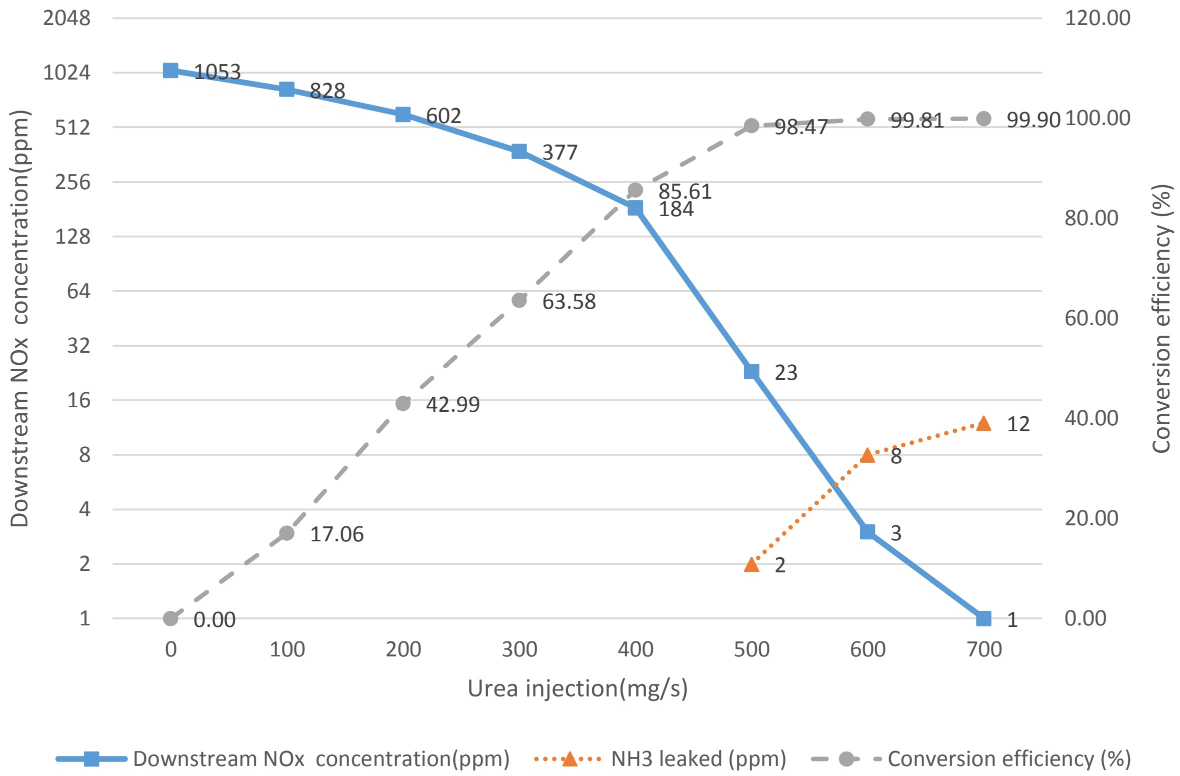

Fig. 4. The relationship between urea injection and NO_x conversion efficiency under Case 5.

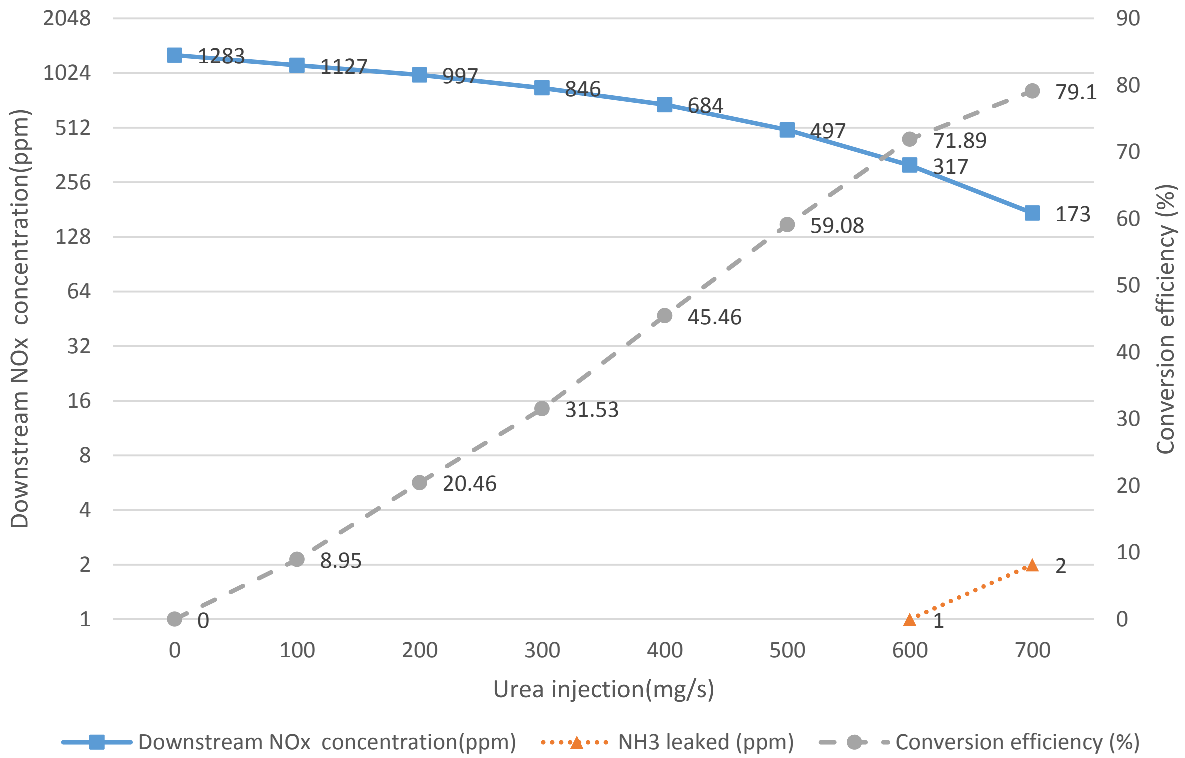

Fig. 5. The relationship between urea injection and NO_x conversion efficiency under Case 6.

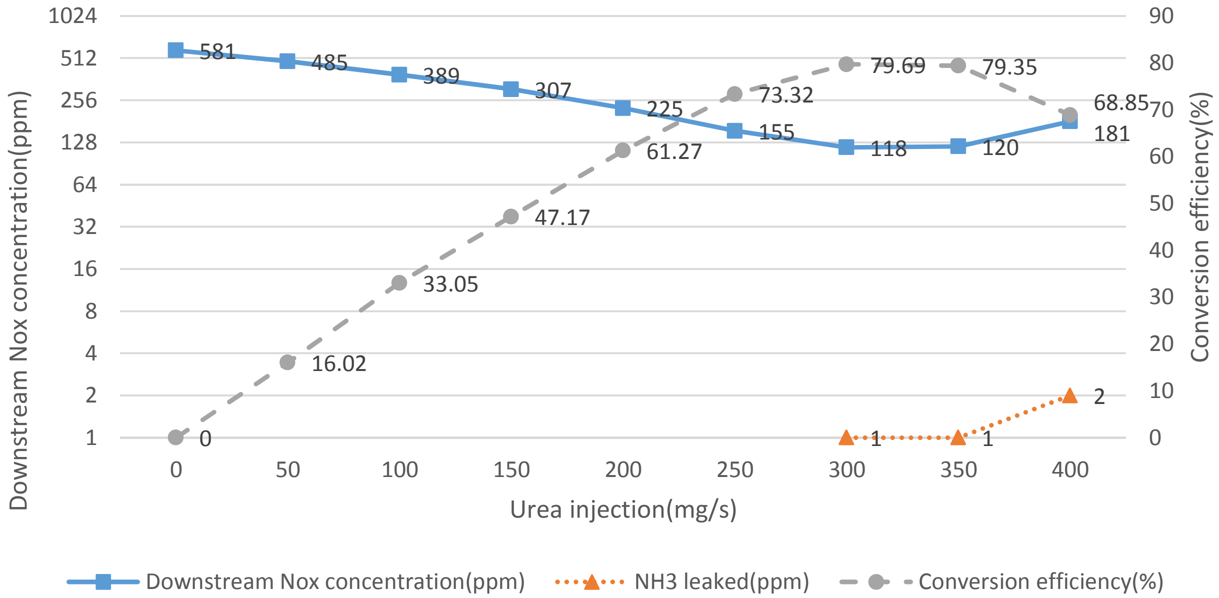

Fig. 6. The relationship between urea injection and NO_x conversion efficiency under Case 9.

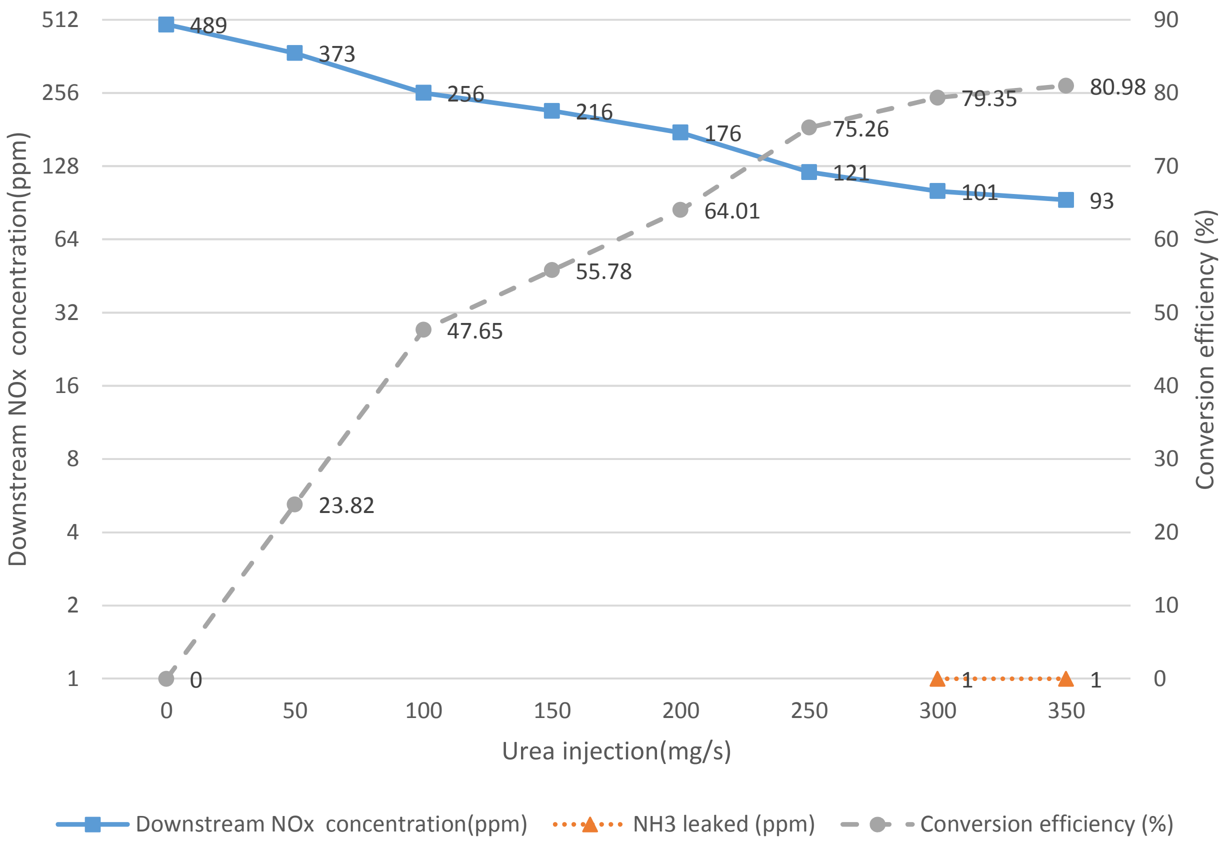

Fig. 7. The relationship between urea injection and NO_x conversion efficiency under Case 11.

And in the condition 5 of BOSCH, the NO_x concentration dropped to 1 ppm from 1053 ppm, it purified a large number of NO_x, but the NH3 leakage content takes a maximum of 12 ppm among these 7 conditions. In the condition 6 of BOSCH, the NO_x concentration dropped to 173 ppm from 1283 ppm, and the NH3 leakage content was only 2 ppm. The difference of NO_x was the minimum of 396 ppm in the condition 11, and the NH3 leakage content was also the minimum of 1 among these conditions. In the condition 9 of BOSCH and condition 5, 9 of KDS, respectively, when the urea injection quantity reached 300 ppm, 550 ppm, 300 ppm, the turning point appeared, the downstream NO_x

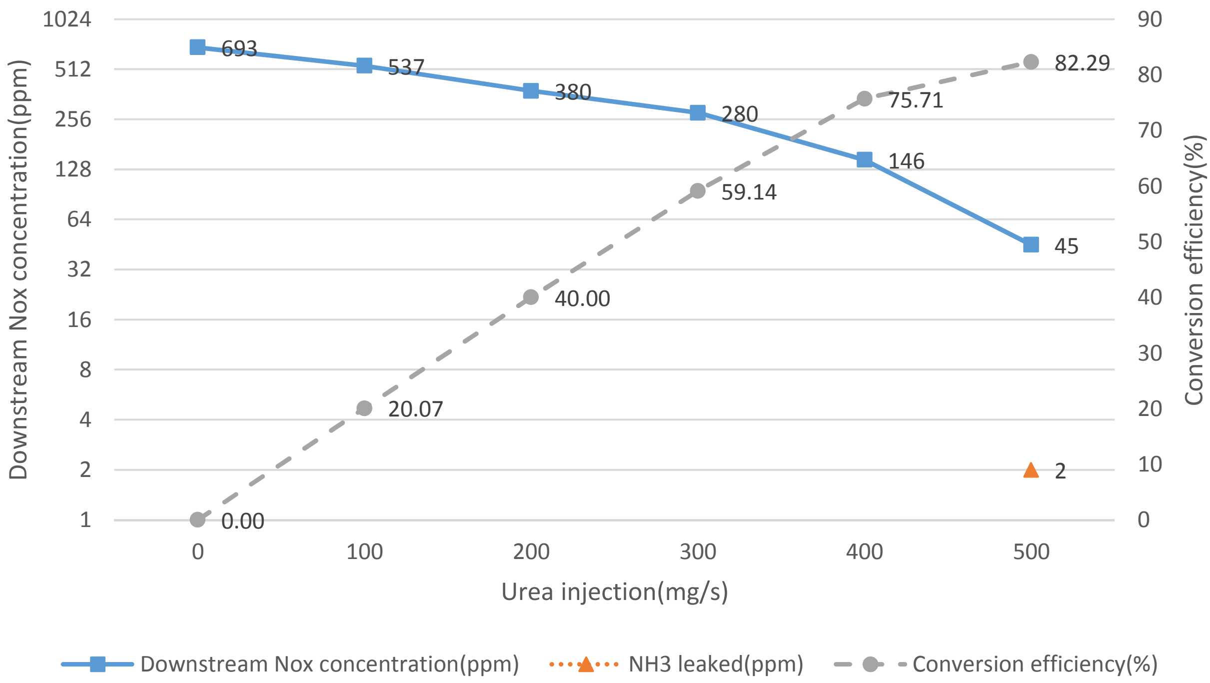

Fig. 8. The relationship between urea injection and NO_x conversion efficiency under Case 13.

concentration started to rise, the conversion efficiency began to decrease, but the variation tendency of NH_3 leakage content didn't change.

Conversion Efficiency Analysis of SCR System Based on KDS Pump and BOSCH Pump

As one of the core components of the SCR system, urea pump is a device that delivers urea solution to a urea nozzle, mainly integrated by the pump unit, the driving unit, the electronic control unit, the valve control unit and auxiliary components and so on. According to the different ways of atomization, urea pump can be divided into air-assisted and air-free type. The air-assisted urea pump is a device that delivers a precisely metered urea solution to the nozzle by means of compressed air. The airless auxiliary urea pump is a device that delivers a urea solution with a stable pressure to the nozzle. In this experiment, KDS pump and BOSCH pump were used to analyze the conversion efficiency of SCR system. Urea pump has five working conditions: stop, fill, work, emptying, diagnosis. When the ECM (Engine Control Module) detects that the engine is started, the ECM will send a filling command to the system, and the system will begin filling after receiving the filling command. The system will be metered and supplied in accordance with the amount of urea required by the ECM, while still having compressed air flowing out of the nozzle atomizing the urea solution. When the ECM/DCU detects that the engine is shutting down, it sends an empty command to the system in 200 ms intervals until the system replies emptying completed. The results are shown in Figs. 9–15.

From the comparison of Fig. 9 to Fig. 15, it can be revealed that the conversion efficiency of BOSCH in case 5 is greater than that of KDS. As the amount of urea injection increases, the difference between the two pumps decreases gradually. When the urea injection reaches 700 ppm, BOSCH and KDS conversion efficiency has both reached 99.90%. In the case of 3, 6, 11, 13, KDS is always greater than BOSCH. The difference between KDS and BOSCH in working condition 3 decreased with the increase of urea injection. When the amount of urea is 500, the conversion efficiency of BOSCH is 1.23% higher than that of KDS. In the case of 6, 11, 13, the conversion efficiency of KDS is significantly higher than that of BOSCH, which is 86.03% 88.82% and 94.94%, when the urea injection reaches 700 ppm, 350 ppm, 500 ppm, respectively, and the difference value between KDS and BOSCH is 6.79%, 7.84%, 12.65%. In the case 4, 9, when the value of urea injection is low, KDS is higher than BOSCH, and with the increase of urea injection, the conversion efficiency of BOSCH gradually exceeds KDS, but the difference is not more than 1%. Overall, KDS pump and BOSCH performance was not much difference, KDS pump is slightly higher than BOSCH at high speed.

DISCUSSION

Nitrogen oxide reduction efficiency and ammonia slip are two main parameters that affect SCR system performance (Winkler *et al.*, 2003; Cheruiyot *et al.*, 2017). Naseri and others evaluated the system consisting of SCR-DPF as compared to the DOC + CSF (Catalytic Soot Filter) component of the DOC + CSF + SCR system on the engine EGR. CSF is used for diesel exhaust soot filtration and accumulated soot is periodically combusted to regenerate CSF. The heat required for soot regeneration is supplied from the DOC pre-catalyst in a particular regeneration mode. Additional fuel is supplied to the DOC through post-injection and/or fueling into the exhaust pipe upstream of

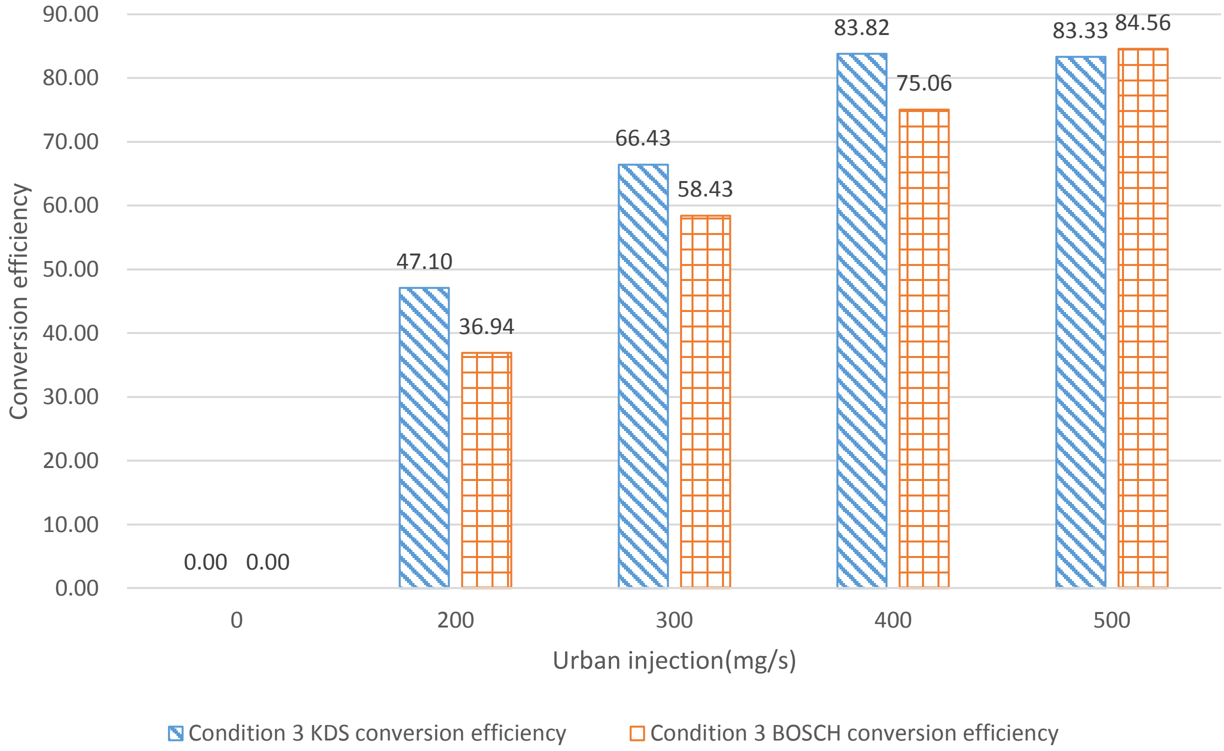

Fig. 9. The comparison between KDS and BOSCH system conversion efficiency under Case 3.

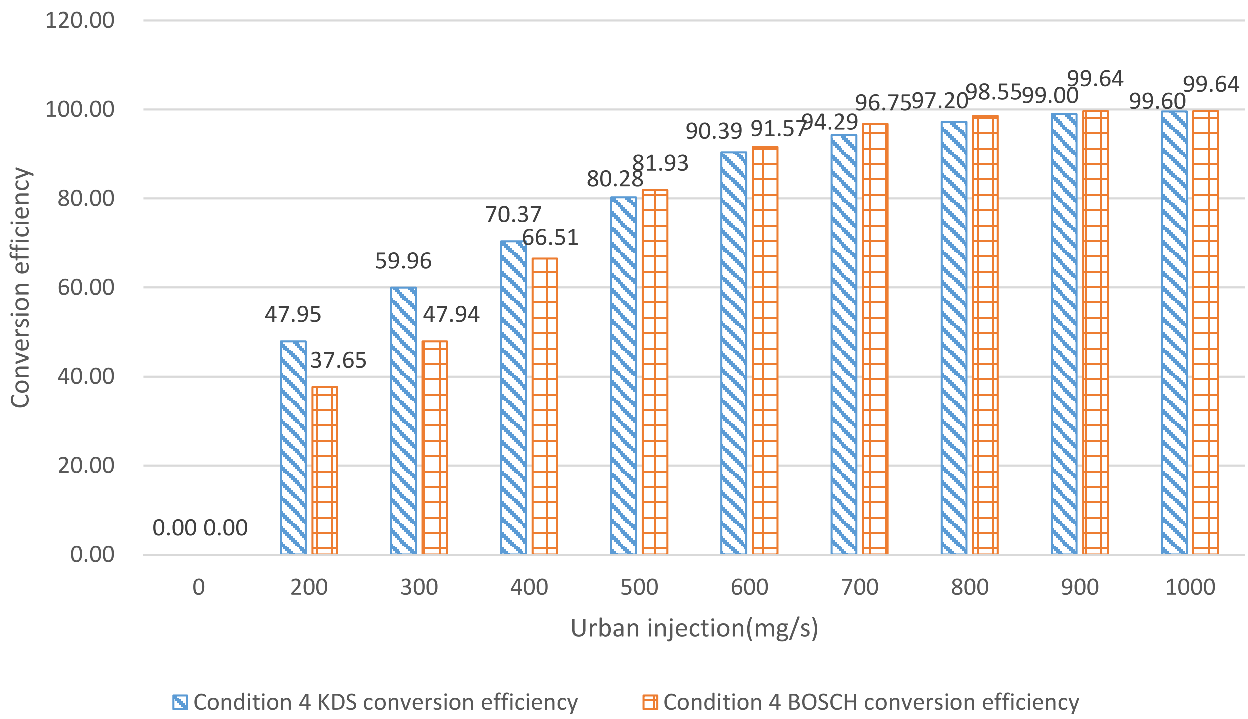

Fig. 10. The comparison between KDS and BOSCH system conversion efficiency under Case 4.

the DOC. The resulting exotherm provides heat for soot combustion on the CSF. Uniform and controlled soot combustion in CSF is necessary to maintain system durability during vehicle life. And the analysis shows that the SCR-DPF system exhibits significantly higher NO_x reduction efficiency than the CSF system in steady-state and heavy-duty FTP (Federal Test Procedure) transient conditions when the engine is operating under the same conditions. At 400°C, net soot oxidation (i.e., the soot removed from the filter is more than the soot removed from the engine) is observed on the SCR-DPF system, possibly because when the engine EGR is closed, the NO_x/PM is high. The high passive filter regeneration activity of the SCR-DPF system operating at high engine output NO_x may result in less frequent active regeneration events and thus reduced fuel losses associated with active regeneration. This result shows that the use of the SCR-DPF system not only meets the current NO_x reduction

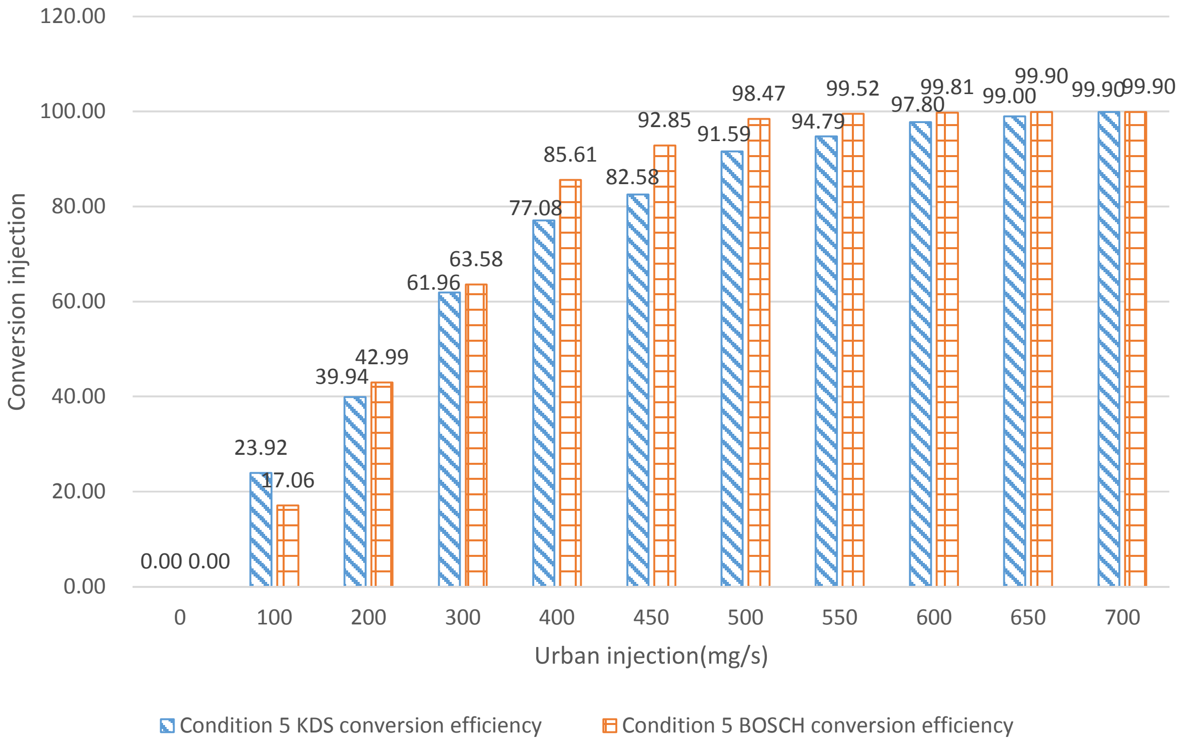

Fig. 11. The comparison between KDS and BOSCH system conversion efficiency under Case 5.

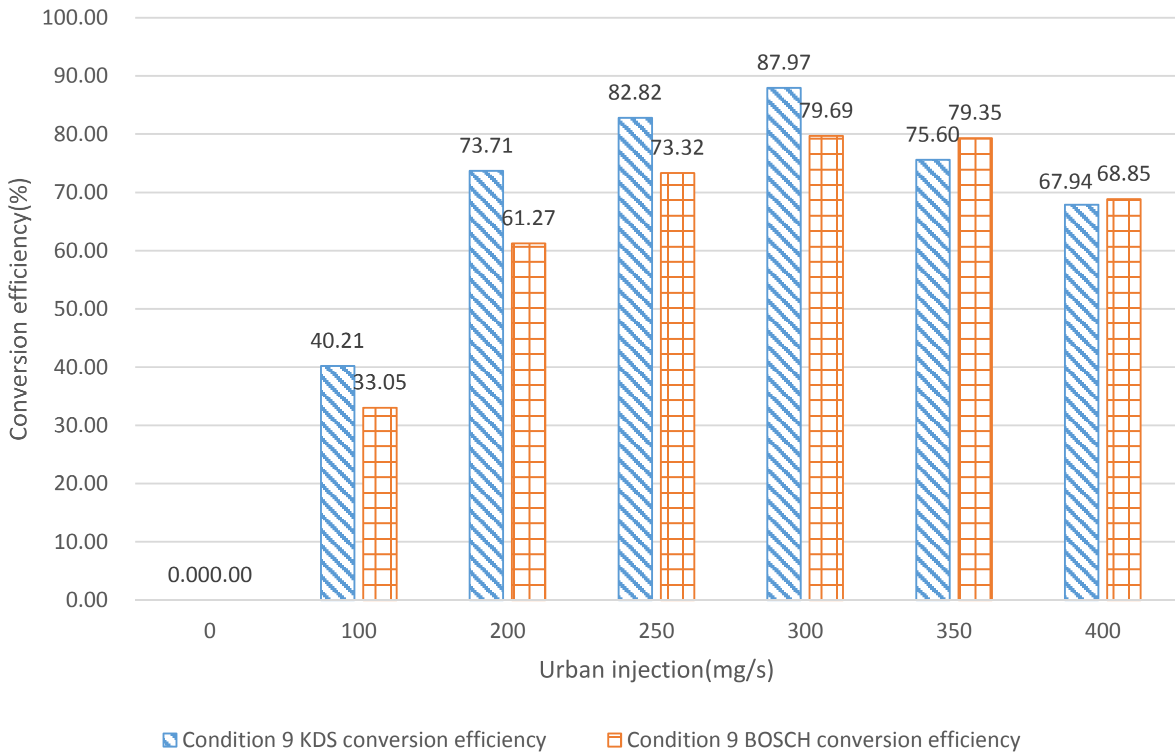

Fig. 12. The comparison between KDS and BOSCH system conversion efficiency under Case 9.

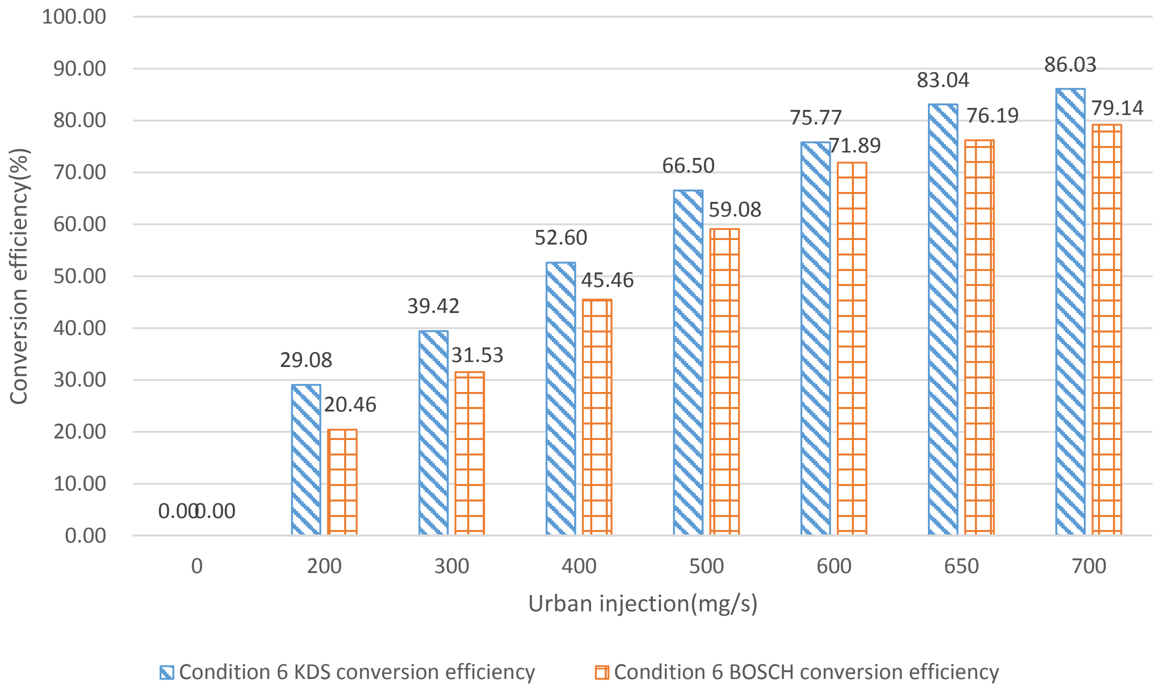

Fig. 13. The comparison between KDS and BOSCH system conversion efficiency under Case 9.

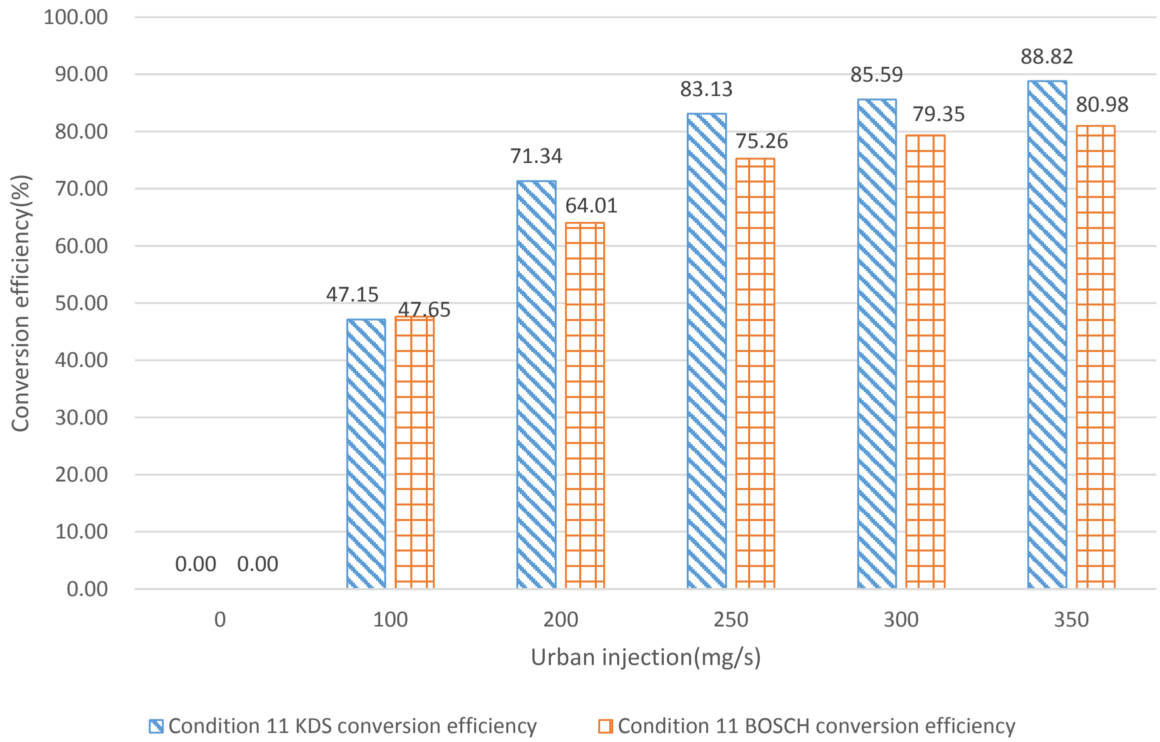

Fig. 14. The comparison between KDS and BOSCH system conversion efficiency under Case 11.

requirements but also improves the fuel economy of heavy-duty diesel vehicles by allowing it to operate at higher engine output NO_x conditions, reducing fuel losses associated with active regeneration (Naseri *et al.*, 2011). Cu-based catalyst and Fe-based catalyst in urea SCR systems were investigated by Nishiyama *et al.* (2015). It was found that in the combined SCR system and under various operating conditions, different catalyst systems were performed transient engine testing to analyze of NO_x reduction efficiency It found that the combined SCR system can be more effective than the individual Fe-SCR or Cu-SCR to reduce NO_x. The optimum NO_x reduction

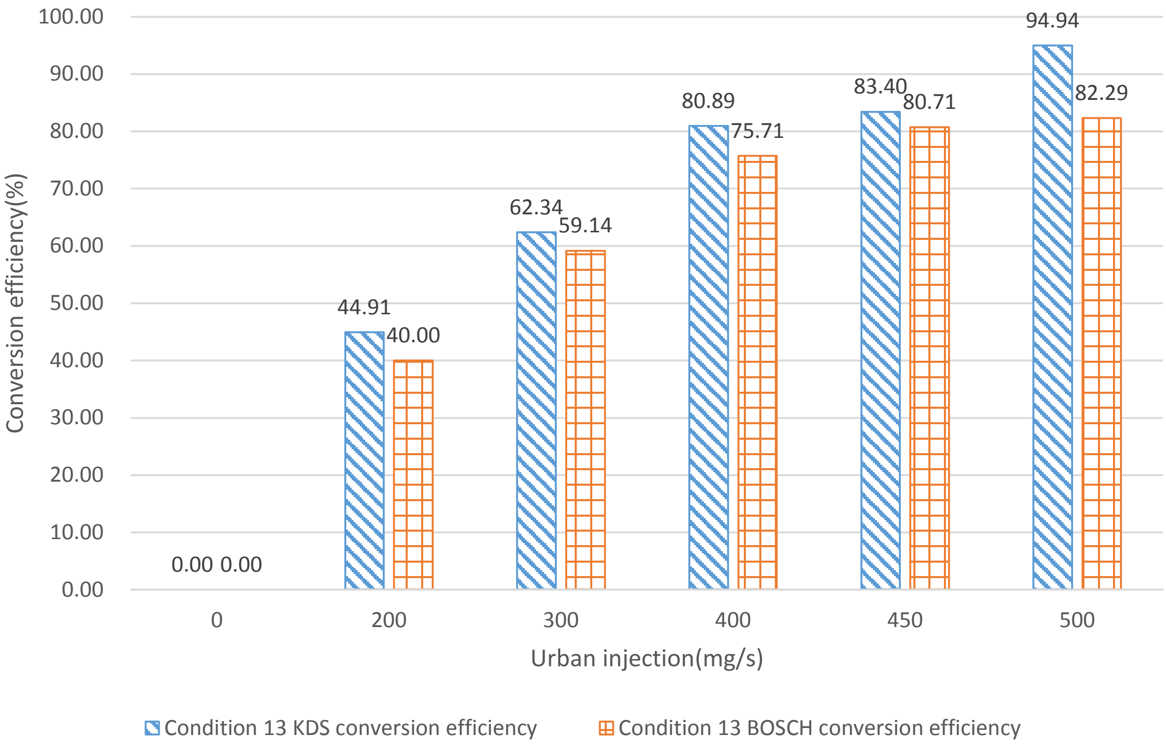

Fig. 15. The comparison between KDS and BOSCH system conversion efficiency under Case 13.

performance was achieved at a Cu ratio of 0.667 (Fe:Cu = 1:2) (Nishiyama *et al.*, 2015).

NO_x emissions concentration of diesel engine under different conditions is different. For example, if the speed of diesel engine is the same, the increase in the diesel engine load conditions results in the gradual increases in the concentration of NO_x emissions. In this study, it used DOC + DPF combined section, i.e., catalytic oxidation bed system, which is to improve the stability and robustness of pure SCR system. It is found that the improved catalytic oxidation bed system provides significant removal efficiency for the exhaust NO_x of the diesel engine under various operating conditions. When the removal rate reaches the highest, the downstream NO_x concentration is only 1 ppm. The NO_x conversion efficiency can be achieved 79.10% or more, the maximum even reaches 99.90%. While retaining most of the other gas pollutants, such as CH, PM, CO and so on, so that through the DOC + DPF combined section, the exhaust gas composition is much cleaner than before. In the rear SCR deNOx system, the maximum efficiency of the NO_x removal under the condition ESC5 has reached 99.90%. It was found that the downstream NO_x concentration was significantly improved while the urea injection rate was increasing. And the removal efficiency is also increasing, of which the highest achievable removal efficiency reached 99.9%. Therefore, the use of the SCR deNOx system equipped with post-processing DOC + DPF combined section in the bench experiment has a more efficient NO_x conversion efficiency, the next step can continue to study in the actual application of NO_x conversion efficiency analysis has important reference value.

To achieve the goal of enhancing the purification efficiency of the SCR system, it is necessary to enhance the reduction of nitrogen oxides and control the loss of ammonia. Nishiyama suggests that these two factors can be improved by introducing a mixture of homogeneous ammonia at the SCR inlet (Nishiyama *et al.*, 2015). And Nishiyama record the various parameters that affect the accuracy of the mixture uniformity at the SCR inlet in the mathematical simulation (Nishiyama *et al.*, 2015). Through discussing the uncertainty involved in these modeling and input parameters, and many possible ways are proposed to determine the values in the mathematical model (Nishiyama *et al.*, 2015). Zheng and others study on the specific case study of the initial design layout of parts of urea SCR. The CFD method is used to simulate the phenomenon of urea spray transport, evaporation and droplet wall. Testing the engine dynamometer is to verify the initial design. The urea deposition location in the test was compared with the CFD prediction results. By further analysis and comparison, three kinds of geometric shape urea SCR system were studied to solve the deposition problem. A variety of influencing factors are analyzed synthetically, such as wall temperature and mixers, to determine the optimal design (Zheng *et al.*, 2014).

Secondly, it is found that the conversion efficiency and the injection quantity are nonlinear when analyzing the urea injection rate and NO_x conversion efficiency of the SCR spray ammonia system based on the improved equipment. In the case of the BOSCH operating conditions 9 and the KDS operating conditions 5 and 9, there is a tendency that the conversion efficiency decreases as the urea injection amount increases to a certain value and the downstream NO_x concentration increases. Therefore, timely and appropriate amount of urea injection can take into account the contradiction between NO_x emissions and NH_3 leakage. If urea injection amount of the system is too small, resulting in NO_x conversion efficiency reduced, it's likely to cause excessive emissions of NO_x; however, it is not always better with the greater urea injection amount of system. Too much injection will affect the amount of NO_x conversion efficiency. The excessive urea is not involved in the reduction of NO_x chemical reaction. It will not reach the best efficiency but result in ammonia escape and the formation of secondary pollution emissions. In a practical view, the best choice of injection ratio needs to be based on various affecting factors to achieve the best efficiency. Appropriate injection strategy can shorten the calibration matching cycle to improve work efficiency, but also saving urea consumption after reaching the national emission regulations. Finally, comparing and analyzing the conversion efficiency of SCR system of KDS pump and BOSCH pump, it is found that there is little difference between the two pumps under most of the working conditions, and KDS is a little better than BOSCH under some specific conditions. Therefore, it chooses KDS pump as much as possible.

CONCLUSION

The study shows that using the SCR exhaust post-treatment can reduce emissions of NO_x so that heavy-duty diesel engines fulfill the national emission standards. Remote testing obtained improved results for SCR system emissions from NO_x data, but the ultimate purpose of the SCR technology is to apply it to the diesel engine, the actual operation of which is influenced by changing boundary conditions and more complex variables. At present, the difficulty of SCR system for open-loop control is to set the control strategy of steady-state reducing agent dosage and to adjust the steady-state reducing agent control strategy according to the dynamic distribution of engine exhaust back pressure to suit the transient condition. To this end, further study is needed to research the characteristics of the SCR-system diesel-engine emissions and the exhaust back-pressure distribution of urea aqueous solution temperature on the impact of the flow rate of the device and the different conditions of the catalyst storage capacity of ammonia. In addition, the application of the diesel-engine SCR system and the influence of the dynamic distribution of the exhaust pressure in the test environment requires more study.

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