Experimental Research on Distribution Characteristics of NO\textsubscript{x} Conversion Efficiency of a Diesel Engine SCR Catalyst

Zhancheng Wang, Huiyong Du, Ke Li, Jiaxuan Miao, Min Li,* and Bin Xu

ABSTRACT: An experimental investigation of the distribution characteristics of NO\textsubscript{x} conversion efficiency inside a selective catalytic reduction system is presented in this paper. Wash-coated and extruded vanadium-based selective catalytic reduction catalysts were investigated under an ANR (ammonia nitrogen ratio) of 1.0 and various exhaust gas temperature and flow rate conditions. A moveable sampling probe was located at various measuring points on the exit cross section of the selective catalytic reduction catalyst shell, and the final distribution maps of NO\textsubscript{x} conversion efficiency were obtained by the interpolation of measured data. The experimental result showed that the distribution of NO\textsubscript{x} conversion efficiency of the wash-coated selective catalytic reduction catalyst at the exit cross section was extremely nonuniform and the efficiency of the extruded SCR catalyst was uniform with a higher distribution at the center. A comparison experiment with 180° rotation of the selective catalytic reduction catalysts was implemented, and the efficiency distribution map of the wash-coated selective catalytic reduction catalyst also rotated 180° but that of the extruded selective catalytic reduction catalyst remained unchanged. The uniformity coefficient of the extruded selective catalytic reduction catalyst was higher than that of the wash-coated selective catalytic reduction catalyst used in this study.

1. INTRODUCTION

Selective catalytic reduction (SCR) is the most important technology to make a diesel engine meet the increasingly stringent NO\textsubscript{x} emission regulations.\textsuperscript{1} The working process of an SCR aftertreatment system is complex and changeable. The main factors affecting the NO\textsubscript{x} conversion efficiency are ammonia concentration distribution, exhaust conditions, catalyst activity, and so on.

Wardana et al. used two kinds of urea injection devices to study the ammonia uniformity of an SCR system.\textsuperscript{2} At the same time, the ammonia uniformity and urea injection time were studied to predict the NO\textsubscript{x} reduction efficiency of an SCR system.\textsuperscript{3,4} Ehson et al. realized the chromatographic measurement of ammonia concentration in a diesel engine exhaust.\textsuperscript{5} Stritzke et al. used a tunable diode laser absorption spectrometer (TDLAS) to study the ammonia concentration distribution characteristics.\textsuperscript{6} Gis et al. used a laser diode spectrometer (LDD) and a Fourier transform infrared spectrometer (FTIR) to measure ammonia concentration in diesel exhaust gas.\textsuperscript{7} Zhen et al. found that the installation of a mixer can improve the uniformity of ammonia concentration distribution and NO\textsubscript{x} conversion efficiency.\textsuperscript{8} McKinley et al. proposed that improving the uniformity coefficient of flow field and gas-phase components can improve NO\textsubscript{x} conversion efficiency and reduce ammonia leakage.\textsuperscript{9} Paramadyalan and Pant studied the effect of ammonia mole fraction distribution on NO\textsubscript{x} conversion efficiency through modeling.\textsuperscript{10} Kalyankar et al. proposed a transient weighted uniformity coefficient. When the weighted uniformity coefficient increases, the NO\textsubscript{x} conversion efficiency increases.\textsuperscript{11} An-dong et al. and Jing et al. used Fire software to establish and verify the model of an SCR catalyst.\textsuperscript{12,13} Through calculation and analysis, the effects of temperature, space velocity, ammonia nitrogen ratio, and NO/NO\textsubscript{2} molar ratio on the molar fraction field in the SCR catalyst were studied. Yun-jing et al. used Fire software to simulate a model and verified it through experiments to study the impact of structural changes on conversion efficiency.\textsuperscript{14} Qian et al. used Fire software to simulate and study the influence of a premixer on NO\textsubscript{x} conversion efficiency and compared and analyzed the optimal mixer structure.\textsuperscript{15} Qiu et al. studied the exhaust temperatures upstream and downstream of a catalyst under steady-state and transient conditions.\textsuperscript{16} Hong conducted an experimental study on the uniformity of the temperature field in a catalyst under steady-state and transient conditions.\textsuperscript{17}
A catalyst, as the most important part of an SCR system, directly affects the NO\textsubscript{x} conversion efficiency of the system. The preparation methods of catalysts can be divided into a coating method and an extrusion method.\textsuperscript{18} Commercial catalysts were mainly prepared by the impregnation coating method. Microscopic images of the catalyst surface were obtained by scanning electron microscopy (SEM),\textsuperscript{19} and their uniformity was determined through observation.

Most of the research studies on SCR conversion efficiency in the existing literature measure the efficiency of the system in the exhaust pipe downstream of the catalyst. Considering that the above parameters are not evenly distributed and there may be an uneven distribution of active components in the coated catalyst, it is necessary to study the distribution characteristics of NO\textsubscript{x} conversion efficiency in the SCR catalyst. It has guiding significance for improving the production process of catalysts and further improving the conversion efficiency of SCR systems.

2. TEST EQUIPMENT AND METHOD

2.1. Test Equipment. A nonroad stage IV diesel engine is used as the test platform, and the technical parameters of the diesel engine are shown in Table 1. The following instruments were used in this study: a Hunan Xiangyi GW250 eddy current dynamometer, a fuel consumption meter, a fuel temperature and cooling water temperature control device to control the engine working condition, and a MEXA-7100DEGR emission analyzer (Japan HORIBA Ltd.) to measure the NO\textsubscript{x} concentration in the exhaust.

The schematic diagram of the test bench is shown in Figure 1. A stainless steel exhaust pipe with a diameter of 102 mm is connected to the turbine outlet of the diesel engine. In the direction of exhaust flow, a urea nozzle, pressure transmitters, thermocouple, SCR catalyst, sampling pipe, and emission analyzer connected to the sampling pipe are arranged in turn. The urea nozzle is installed at the elbow of the exhaust pipe, and the elbow angle is 90°. The distance between the urea nozzle and catalyst inlet section is 600 mm, and the exhaust pipe and catalyst are fixed horizontally. Considering that a vanadium-based catalyst is the most commonly used catalyst in modern diesel engines, commercially coated and extruded vanadium-based catalysts (V\textsubscript{2}O\textsubscript{5}-WO\textsubscript{3}/TiO\textsubscript{2}) were used for SCR. The diameter of the catalyst part was 190 mm, the length was 355 mm, the total volume was 10.07 L, and the cell density was 355 mm, the total volume was 10.07 L, and the cell density was 30 CPSI. The urea injection system is a non-air-assisted urea pump with a three-hole water cooling nozzle. There are no mixer, DOC, and DPF in the exhaust system. In the test, China V diesel fuel and 32.5 wt % urea solution were used, which met the standard of GB29518-2013.

| Table 1. Diesel Engine Parameters |
|----------------------------------|
| project                          | parameter                           |
| type of diesel engine            | inline 4-cylinder water-cooled direct injection |
| displacement (L)                 | 4.33                                 |
| air intake mode                  | turbo charge and intercooling        |
| fuel supply system               | electronically controlled high-pressure common rail |
| rated power (kW)                | 82 (2200 r·min\textsuperscript{-1}) |
| maximum torque (N·m)             | 462 (1600 r·min\textsuperscript{-1})  |
| emission standard                | diesel engines of nonroad mobile machinery (CHINA IV) |

Figure 1. Schematic diagram of the test bench.

2.2. Test Method. To study the distribution characteristics of NO\textsubscript{x} conversion efficiency in the catalyst, a hollow stainless steel sampling tube with an inner diameter of 6 mm and a wall thickness of 1 mm is arranged at the outlet section of the catalyst. The end of the sampling tube is bent to 90° as the inlet of the sampling gas. During the measurement, the inlet of this tube is set close to the outlet section of the catalyst, and the exhaust gas can enter the sampling tube immediately after leaving the honeycomb channel of the catalyst. The other end of the sampling pipe is connected to an emission analyzer to measure the NO\textsubscript{x} concentration in the exhaust gas. The sampling tube can be moved to adjust the radial position of the measuring point. To avoid the measurement error caused by the backflow of the exhaust gas at the outlet of the catalyst, a stainless steel tube with the same diameter as the catalyst shell is used, and the length between the catalyst outlet section and the tapered tube is increased, which is the rotatable sampling section shown in Figure 1. The rotatable sampling section is connected to the shell of the catalyst and the reducing tube through the quick fitting joint, so that it can rotate with the catalyst axis as the axis. That is to say, during the measurement process, the catalyst will not move. The rotatable sampling section adjusts the circumferential position of the sampling tube to adjust the circumferential position of different measurement points. By adjusting the radial and circumferential positions of the measuring points, the NO\textsubscript{x} concentration at each measuring point of the catalyst outlet section can be measured.

Figure 2 shows the distribution of measuring points of the catalyst outlet cross section. The diameter of the catalyst outlet cross section is 190 mm, each diameter is divided into six equal parts, five or seven sampling points are arranged at intervals,
and the included angle between adjacent diameters is 30°. A total of 37 sampling points are arranged, in which a series of sampling points (A1–A7 direction) are in the gravity direction, and the D1 measuring point is in the inner curvature of the exhaust elbow.

During the test, to reduce the fluctuation of the original emission,20,21 when the water temperature and oil temperature of the diesel engine reach the preset values, it is considered that the warm-up procedure is over, and the diesel engine working condition is adjusted to bring the exhaust temperature and flow to the target value. Then, the NOx concentration of each measuring point is measured by the emission analyzer, which can be considered as the original NOx emission concentration at each point. It should be noted that the distribution of the original NOx concentration is measured at the outlet plane of the catalyst.

Figure 3 shows the distribution of NOx at the inlet and outlet planes of the catalyst, which indicated that the NOx concentration measured in the outlet of the catalyst can be considered as the original NOx emission in the inlet of the catalyst. The urea solution is injected into the exhaust gas with an ANR of 1.0, and the NOx concentration at each measuring point is measured after stabilization, that is, the NOx concentration at each measuring point after a catalytic reduction reaction. For each sampling point, the measurement is repeated five times. The standard error of the NOx measurement is less than 3%. According to the two NOx concentrations, the NOx conversion efficiency (η) of each measuring point is calculated as follows

$$\eta = \frac{C_1}{C_2}$$

(1)

where $C_1$ and $C_2$ represent the NOx concentration with and without urea injection. The distribution cloud map of the NOx conversion efficiency of this section is drawn by the interpolation method.

It should be noted that we used only one sampling tube located at the outlet of the SCR catalyst to measure the NOx concentration. In addition, the inlet of the sampling tube is set to be extremely close to the outlet of the SCR catalyst. That is, the diesel exhaust gas would flow into the sampling tube at the moment that it leaves the channel of the SCR catalyst. In this way, although the sampling tube would disturb the exhaust flow, the results of NOx concentration are still credible to characterize the NOx concentration of each sampling location.

The average conversion efficiency $\bar{\eta}$ and uniformity coefficient $\gamma$ are defined, respectively, as follows

$$\bar{\eta} = \frac{\sum \eta_i}{n}$$

(2)

$$\gamma = 1 - \frac{\sum |\eta_i - \bar{\eta}|}{2n\bar{\eta}}$$

(3)

where $\bar{\eta}$ is the NOx conversion efficiency of each measuring point and $n$ is the number of measuring points.

3. TEST RESULTS AND DISCUSSION

3.1. Uniformity of Efficiency Distribution of the Coated Catalyst. As shown in Figure 4, when the exhaust temperature of the coated vanadium-based catalyst (if not specified, the exhaust temperature refers to the average temperature of the catalyst inlet section) is 250 °C, the NOx conversion efficiency distribution characteristics of the catalyst outlet section under different exhaust flow conditions are shown.
It can be seen from Figure 4 that the distribution of NOx conversion efficiency is basically the same under various exhaust flow conditions, and the distribution of NOx conversion efficiency is highly uneven, especially in the upper left corner of the figure; that is, at B1 and C1 (see Figure 2), the conversion efficiency is significantly lower than that of other measurement points. Due to the scale, the efficiency of this area is not shown in the figure, and the actual efficiency of this area is about 20%. There are also two high-efficiency regions (B2, C2 and B6, C6). With the increase of the exhaust flow, the conversion efficiency of each region decreases.

As shown in Figure 5, the average NOx conversion efficiency and uniformity coefficient of the coated catalyst outlet section under different exhaust conditions can be seen. It can be seen that when the exhaust temperature is 350 °C, the average NOx conversion efficiency and uniformity coefficient are the highest. When the exhaust temperature is 250 °C, the average conversion efficiency of NOx is the lowest. When the exhaust temperature is 450 °C, there is a reduction range of uniformity coefficient, and the average conversion efficiency of NOx is the lowest.

This is because the temperature window of the highest activity of the vanadium-based catalyst used in the test is 300–350 °C, and the conversion efficiency at 450 °C is less than 350 °C due to the violent oxidation of ammonia at high temperatures. When the exhaust temperature is 350 °C, the efficiency of all measuring points except B1 and C1 is relatively high, and the average conversion efficiency and uniformity coefficient are the highest. When the exhaust temperature is 250 °C, the catalyst activity is the lowest, so the average conversion efficiency is the lowest. When the exhaust temperature is 450 °C, the selectivity of the catalyst becomes poor and ammonia is oxidized violently, which leads to a large efficiency difference between the measuring points and the lowest uniformity coefficient.

It can be seen from Figure 5 that the average conversion efficiency and uniformity coefficient of NOx decrease with the increase of the exhaust flow rate at different exhaust temperatures, but the average conversion efficiency decreases slightly and the uniformity coefficient decreases sharply at 350 °C. When the exhaust temperature is 250 °C, the decrease of the average conversion efficiency and uniformity coefficient is small. When the exhaust temperature is 450 °C, the average conversion efficiency and uniformity coefficient change substantially with the increase of the exhaust flow rate.

The NOx conversion efficiency is mainly affected by the urea decomposition rate (ammonia concentration), space velocity, and catalyst activity. According to the conclusion of ref 26, in the space velocity range corresponding to the test conditions, the urea decomposition rate decreases significantly with the increase of space velocity at a low exhaust temperature (250 °C) and remains unchanged with the increase of space velocity at high-temperature conditions (350 °C and 450 °C).

Due to the increase of space velocity, the contact time between the exhaust and catalyst is reduced, and the average NOx conversion efficiency is reduced. Because of the uneven distribution of NOx conversion efficiency in the catalyst outlet section, the sensitivity of each region to space velocity is not the same, that is, the decrease range of the low-efficiency region is larger, resulting in a decrease of the uniformity coefficient. When the exhaust temperature is 350 °C, the catalyst activity is higher, the space velocity is increased with the increase of the exhaust flow rate, and the average conversion efficiency is slightly decreased. Compared with the exhaust temperatures of 250 and 450 °C, the reduction range of the low-efficiency zone is larger, and the uniformity coefficient is sharply decreased. When the exhaust temperature is 250 °C, the decomposition rate of urea is low at each exhaust flow rate. Although the ANR is 1.0, the overall ammonia in the catalyst is insufficient, and the activity of the catalyst is also low. With the increase of the exhaust flow rate, the conversion efficiency of each measuring point decreases substantially, resulting in small changes in the average conversion efficiency and uniformity coefficient. When the exhaust temperature is 450 °C, the average conversion efficiency is sharply decreased. When the exhaust temperature is 250 °C, the catalyst activity is the lowest, so the average conversion efficiency is the lowest.
efficiency decreases due to the increase of space velocity and the increase of ammonia oxidation at high temperatures, while the uniformity coefficient decreases between 250 and 350 °C.

### 3.2. Uniformity of Active Components of the Coated Catalyst

To determine the cause of the abnormal nonuniform distribution of NO\textsubscript{x} conversion efficiency at the outlet section of the catalyst, the catalyst was rotated 180° around its axis and the repeated measurement was carried out under the same diesel engine running conditions and exhaust pipe arrangement. When the exhaust temperature is 250 °C and the exhaust flow rate is 250 kg·h\textsuperscript{-1}, the results are shown in Figure 6, which is a comparison of the NO\textsubscript{x} conversion efficiency cloud chart distribution before and after the catalyst is rotated.

Figure 6 shows the NO\textsubscript{x} conversion efficiency distribution before and after catalyst rotation. That is, after rotation of the catalyst, the NO\textsubscript{x} conversion efficiency distribution in Figure 6a is rotated 180°, which is basically consistent with Figure 6b.

The arrangement of the exhaust pipe is not changed in the test, and the honeycomb cell of the catalyst is uniformly distributed. It can be considered that after the catalyst rotates 180°, the exhaust pipe and catalyst remain unchanged, and the diesel engine operating conditions and urea injection parameters also remain unchanged. If there is no blockage in the catalyst channel, it can be considered that the distribution of the temperature field, flow field, and ammonia concentration inside the catalyst also remain unchanged.

The NO\textsubscript{x} distribution characteristics before and after the catalyst rotation under other different exhaust conditions were also measured. It will not be repeated here. The NO\textsubscript{x} conversion efficiency distribution of the catalyst outlet section moves to the corresponding position with the catalyst rotation. Considering that the employed catalyst has a circular shape, the rotation of the catalyst has a negligible effect on the flow distribution of NO\textsubscript{x} and NH\textsubscript{3}. Thus, it can be inferred that the reason for this low efficiency is the poor distribution of active components.

Based on the above conclusion, it is inferred that the uneven distribution of NO\textsubscript{x} conversion efficiency in Figure 4 is due to the uneven distribution of active components of the catalyst, and the extremely low efficiency in the upper left corner of Figure 4 is due to the poor coating quality of active components of the catalyst in this area.

The commercial coated catalyst used in this experiment exhibits the phenomenon of uneven distribution of active components, and the uniformity of active components has a great influence on the conversion efficiency distribution. Considering the process of the coated catalyst, most coated catalysts may have this defect. The test method in this paper can be used to detect the distribution uniformity of active components of the catalyst. For the coated catalyst used in this test, the overall NO\textsubscript{x} conversion efficiency is acceptable\textsuperscript{33} but there are some defects in some parts, indicating that the coating process can still be improved. The test method
proposed in this paper has guiding significance for improving the production process of catalysts and further improving the NO\textsubscript{x} conversion efficiency of SCR systems.

3.3. Uniformity of Efficiency Distribution of the Extruded Catalyst. Using the same size of the extruded vanadium-based catalyst, adjusting the engine operating conditions to make the exhaust temperature 250 °C, exhaust flow 250 kg h\textsuperscript{-1}, and ANR 1.0, the NO\textsubscript{x} conversion efficiency distribution of the catalyst outlet section before and after 180° rotation of the catalyst was measured, as shown in Figure 7. It can be seen from the figure that the distribution of NO\textsubscript{x} conversion efficiency before and after catalyst rotation is almost the same, which indicates that the distribution of active components of the extruded catalyst is more uniform. The distribution of conversion efficiency is high in the center and low in the edge and reaches the lowest in a small range near the wall, with a maximum difference of 11%. There are three small areas with higher efficiency in the central efficiency area. This is because the temperature distribution center of the catalyst inlet section is high and the edge is low,\textsuperscript{6} which leads to a higher urea decomposition rate and higher ammonia concentration in the mainstream area. Moreover, due to the higher temperature in the mainstream area, the catalyst activity is high and the central NO\textsubscript{x} conversion efficiency is higher. A three-hole non-air-assisted urea injector was used in this test. The three more efficient regions in the center in Figure 7 correspond to the three urea spray drops, where the ammonia concentration is higher, resulting in the highest NO\textsubscript{x} conversion efficiency in the area.

Compared with the coated catalyst, the extruded catalyst mixes the active components and the support evenly and extrudes them directly.\textsuperscript{27} The active components are evenly distributed, and the NO\textsubscript{x} conversion efficiency distribution is affected by the exhaust temperature, flow field, and ammonia concentration distribution. Since it is impossible to guarantee the consistency of the two catalysts, only the uniformity coefficient of NO\textsubscript{x} conversion efficiency of the coated and extruded catalysts is compared, as shown in Table 2.

Table 2. Comparison of the Uniformity Coefficient between Coated and Extruded Catalysts

| exhaust temperature (°C) | exhaust flow (kg h\textsuperscript{-1}) | uniformity coefficient | coated | extruded |
|--------------------------|--------------------------------------|-----------------------|--------|---------|
| 250                      | 250                                  | 0.9455 ± 0.0283       | 0.9812 ± 0.0294 |
| 250                      | 350                                  | 0.9430 ± 0.0282       | 0.9763 ± 0.0292 |
| 250                      | 450                                  | 0.9418 ± 0.0282       | 0.9754 ± 0.0292 |

It can be seen from Table 2 that the uniformity coefficient of the extruded catalyst is significantly higher than that of the coated catalyst because the active components of the extrusion catalyst are distributed uniformly, there is no coating defect in the coated catalyst for this test, and the NO\textsubscript{x} conversion efficiency distribution at the outlet section of the catalyst is more uniform.

4. CONCLUSIONS

(1) The NO\textsubscript{x} conversion efficiency distribution at the outlet section of a commercially coated vanadium-based catalyst is very uneven, and the local conversion efficiency is as low as 20%. When the exhaust temperature is 350 °C, the average conversion efficiency and uniformity coefficient are the highest. With the increase of the exhaust flow, the average conversion efficiency and uniformity coefficient decrease. The results show that the NO\textsubscript{x} conversion efficiency distribution of an extruded catalyst is high in the center and low in the edge.

(2) On comparing the catalysts before and after 180° rotation, the results show that the distribution of active components in the coated catalyst is not uniform, while that in the extruded catalyst is more uniform. The distribution uniformity of active components has a great influence on NO\textsubscript{x} conversion efficiency.

(3) The results of this paper provide a method to detect the distribution of NO\textsubscript{x} conversion efficiency of SCR catalysts, which suggest that the manufacturers have to focus on the overall conversion efficiency of SCR catalysts. The results can also help further improve the efficiency of SCR catalysts.

AUTHOR INFORMATION

Corresponding Author
Min Li – Vehicle & Transportation Engineering Institute, Henan University of Science and Technology, Luoyang 471003, China; Phone: +86-13949219654; Email: zcwzh@126.com

Authors
Zhancheng Wang – Vehicle & Transportation Engineering Institute, Henan University of Science and Technology, Luoyang 471003, China; orcid.org/0000-0002-2862-0960
Huiyong Du – Vehicle & Transportation Engineering Institute, Henan University of Science and Technology, Luoyang 471003, China
Ke Li – Gu an Dinos Environmental Protection Equipment Manufacturing Co., Ltd, Beijing 065000, China
Jiaxuan Miao – Vehicle & Transportation Engineering Institute, Henan University of Science and Technology, Luoyang 471003, China
Bin Xu – Vehicle & Transportation Engineering Institute, Henan University of Science and Technology, Luoyang 471003, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c02396

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The authors express their gratitude to The National Key Research and Development Program of China (Project no. 2016YFD0700700) and Bilingual Teaching Project of Henan University of Science and Technology (Emissions from Internal Combustion Engine) for financial support.

REFERENCES

(1) Boulter, P. G.; Borken-Kleefeld, J.; Ntziachristos, L. The Evolution and Control of NO\textsubscript{x} Emissions from Road Transport in Europe. In Urban Air Quality in Europe; Springer: Berlin, Heidelberg, 2013; Vol. 26, pp 31–54.
(2) Wardana, M.; Oh, K.; Lim, O. Investigation of Urea Uniformity with Different Types of Urea Injectors in an SCR System. *Catalysts* 2020, 10, 1269.

(3) Wardana, M.; Shahriar, G. M. H.; Oh, K.; Lim, O. Ammonia Uniformity to Predict NOx Reduction Efficiency in an SCR System. *Int. J. Automot. Technol.* 2019, 20, 313–325.

(4) Wardana, M. K. A.; Oh, K.; Lee, Y. J.; Woo, Y. M.; Lim, O. Effects of Urea Injection Timing on Predicting NOx Conversion in SCR Systems. *Int. J. Automot. Technol.* 2020, 21, 137–145.

(5) Nasir, E. F.; Nasir, S. T. Laser absorption tomography for ammonia measurement in diesel engine exhaust. *Appl. Phys. B* 2020, 126, No. 178.

(6) Stritzke, F.; Van d, K. S.; Feiling, A.; et al. Ammonia concentration distribution measurements in the exhaust of a heavy duty diesel engine based on limited data absorption tomography. *Opt. Express* 2017, 25, 8180–8192.

(7) Gis, W.; Zoltowski, A.; Grzelak, P. Research on the ammonia concentration in the exhaust gas of the self-ignition engines. *Combust. Engines* 2013, 154, 575–580.

(8) Zhen, C.; Guodong, L.; Yanguang, Z.; et al. Experiment and simulation of ammonia distribution uniformity for diesel engine urea-SCR. *Veh. Engine* 2012, 198, 41–45.

(9) McKinley, T. L.; Alleyne, A. G.; Lee, C. F. Mixture non-uniformity in SCR systems modeling and uniformity index requirements for steady-state and transient operation. *SAE Int. J. Fuels Lubr.* 2010, 3, 486–499.

(10) Paramadjanalan, T.; Pant, A. Selective catalytic reduction converter design: The effect of ammonia nonuniformity at inlet. *Korean J. Chem. Eng.* 2013, 30, 2170–2177.

(11) Kalyankar, A.; Munannur, A.; Liu, Z. G. Predictive Modeling of Impact of ANR Non-Uniformity on Transient SCR System DeNOx Performance. *SAE Technical Papers*, 2015.

(12) An-dong, W. A. N. G.; Jun, L. I.; Lu-yan, F. A. N.; et al. Simulation study on the influence factors of concentration field in SCR catalytic converters. *Veh. Engine* 2016, 5, 5–10.

(13) Jing, W. A. N. G.; Qian, W. A. N. G.; hang, X. U.; et al. Automotive diesel engine SCR system NOx conversion efficiency of diesel engine SCR system. *SAE Int. J. Fuels Lubr.* 2010, 3, 453–460.

(14) Yun-jing, J. I. A. O.; Li-wei, J. I.; Yu, F. E. N. G. Influence of the catalytic converter structure on NOx conversion efficiency in diesel Urea-SCR system. *Intern. Combust. Engines J.* 2015, 4, 14–16.

(15) Qian, W. A. N. G.; Du, Z. H. A. N. G.; Zhi-xia, H. E.; et al. Numerical simulation of diesel engine Urea-SCR system and its mixer structure optimization. *Chin. Intern. Combust. Engine Eng.* 2015, 36, 50–57.

(16) Qiu, T.; Li, X.; Liang, H.; et al. A method for estimating the temperature downstream of the SCR (selective catalytic reduction) catalyst in diesel engines. *Energy J.* 2014, 68, 311–317.

(17) Liang, H. Research on Temperature Field Properties of Selective Catalytic Reduction in A Diesel Engine; Beijing Institute Technology: Beijing, 2015.

(18) Qunhai, C.; He, L.; Bin, G.; et al. Investigation of TiCe0.2WO3 coating for selective catalytic reduction. *Chin. Intern. Combust. Engine Eng.* 2016, 37, 86–92.

(19) Shamsutdinova, A. N.; Brichkov, A. S.; Paukshtis, E. A.; et al. Composite TiO2/fiberglass catalyst: Synthesis and characterization. *Catal. Commun.* 2017, 89, 64–68.

(20) Deman, Z.; Shunning, Li; Kai, Li; et al. Influence of coolant temperature on diesel engine emissions. *Trans. CSICE J.* 2010, 28, 510–513.

(21) Choi, K. W.; Kim, K. B.; Lee, K. H. Investigation of emission characteristics affected by new cooling system in a diesel engine. *J. Mech. Sci. Technol.* 2009, 23, 1866–1870.

(22) Weltens, H.; Bressler, H.; Terres, F.; et al. Optimisation of Catalytic Converter Gas Flow Distribution by CFD Prediction. In *International Congress & Exposition*, 1993.

(23) Lee, B. W.; Cho, H.; Shin, D. W.; et al. Characterization and De-NOx activity of binary V2O5/TiO2 and WO3/TiO2, and ternary V2O5-WO3/TiO2 SCR catalysts. *J. Ceram. Process. Res.* 2007, 8, 203–207.

(24) Kröcher, O.; Elsener, M. Chemical deactivation of V2O5/WO3-TiO2 SCR catalysts by additives and impurities from fuels, lubrication oils, and urea solution: I. Catalytic studies. *Appl. Catal., B* 2008, 75, 215–227.

(25) Gang, L.; Chonglin, S.; Wenbin, G.; et al. Preparation of V2O5/WO3/TiO2 catalyst and the properties for urea-selective catalytic reduction in NOx. *J. Eng. Thermophys.* 2008, 29, 1969–1972.

(26) Junyan, M.; Jun, L.; Dawei, Q.; et al. Urea decomposition efficiency of diesel engine SCR system. *Trans. Chin. Soc. Agric. Mach.* 2015, 46, 282–286.

(27) Xuehua, G.; Yingxia, L.; Jian, C.; et al. Research advances in preparation of honeycomb shaped monolithic zeolite catalysts. *Environ. Sci. Technol.* 2014, 37, 70–74.