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The characteristics of ammonia storage and the development of model-based control for diesel engine urea-SCR system

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ABSTRACT

This paper investigates the characteristics of ammonia storage in actual SCR catalyst, which indicates that space velocities (SV), the exhaust temperature and NH_3:NO_X ratio (NSR) have different impacts on the saturated ammonia storage and saturated time. Thus, this paper proposes an embeddable SCR model consisting of a nonlinear ammonia storage model (NAS model) and a multiple variable resistance–capacitance model with time-delay (MVRC model), in order to quantify the ammonia storage and system-out NO_X concentration. After that, a model-based ammonia storage control strategy was developed to strike a better balance between high NO_X reduction efficiency and low ammonia slip.

Introduction

With increasing demands for low engine emissions, the reduction of nitric oxides (NO_X) produced by heavy duty diesel vehicles has become one of the main tasks. Urea-SCR systems performs very well in NO_X reduction, and thus can be served as a technology platform for further improvement. Therefore, urea-SCR system is recognized as the most preferred approach to meeting strict emission standards [1–6].

The urea-SCR is an effective way for NO_X reduction when the engine operates in the steady state condition. However, rapid change of engine loads leads to a rapid change of exhaust temperature, SV and urea dosage, which makes it difficult to obtain expected NO_X reduction and small NH_3 slip simultaneously. Consequently, SCR control remains a great challenge in practice [7–11]. A better way to improve the performance of SCR system is on-board model-based SCR control, which allows a more accurate control of urea dosage. Weibel et al. proposed a NH_3 load control strategy based on the normalized NH_3 load model, which achieved a considerable NO_X reduction and an acceptable small NH_3 slip [12]. Junmin et al. proposed an ammonia storage distribution control method based on continuous stirred tank reactor model (CSTR model), which could effectively reduce SCR-outlet NO_X and NH_3 emissions [13]. Yang et al. proposed a method combining neural network model with Fuzzy PID to meet both NO_X emission requirements and NH_3 slip targets [14]. However, comparing with modeling researches on the discoveries of fundamental SCR reactions, the studies of embeddable models and experimental reports based on actual urea-SCR systems are relatively scarce [15].

This paper investigates the characteristics of ammonia storage in the actual SCR catalyst under different operating conditions of the engine. Then, in this paper, an embeddable SCR model is proposed to describe ammonia storage and transient response of NO_X concentration with the change of engine conditions and urea dosage. After that, a model-based control strategy of urea-SCR system is proposed.

Materials and methods

Experimental setup

The experimental setup consists of a 4.75 L diesel engine (Table 1), a 12 L V_2O_5-WO_3/TiO_2 catalyst, the urea dosing system and a Wuhan Tianlan designed controller. The aftertreatment system is equipped with NO_X sensors and exhaust temperature sensors at both inlet and outlet of the catalyst converter, and an AVL AMA i60 emission analyzer and a Siemens ammonia analyzer

Abbreviations: NSR, NH_3:NO_X ratio; NAS model, nonlinear ammonia storage model; MVRC model, multiple variable resistance–capacitance model with time-delay; St, stability coefficient; SV, space velocities.

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Table 1
Engine information.

Engine model	Parameters
Features	Inline 4-cylinder, CRDI, TCI
Displacement	4.75 L
Cylinder bore × travel	110 mm × 125 mm
Compression ratio	17.5
Rated power	120 kw at 2500 rev/min
Maximum torque	660 Nm at 1200–1600 rev/min

are located at the tailpipe. The schematic of the experimental setup is shown in Fig. 1.

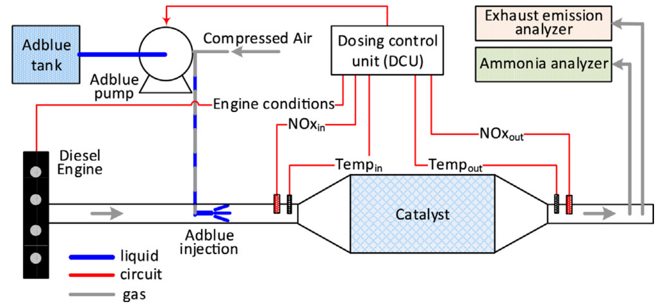

Fig. 1. Engine and urea-SCR aftertreatment system.

Research on the characteristics of ammonia storage

The ammonia storage is defined as the amount of ammonia stored in the catalyst, which can be calculated through the urea dosage, the mass flux and NO_X concentration of engine exhaust, and both the NO_X and NH_3 concentration after the SCR catalyst. The urea dosage is determined by the engine-out NO_X concentration, the NH_3:NO_X ratio, the maximal NO_X conversion efficiency (the NH_3 slip is kept at 10 ppm), the exhaust temperature and mass flux.

The urea dosage and ammonia storage are calculated by Eqs. (1) and (2):

$$V_{urea} = \frac{MG_{urea} \times v \times M_{exh} \times NO_{X,In} \times C_{max} \times NSR}{MG_{exh} \times \rho_{urea} \times MF_{urea} \times 10^5} \quad (1)$$

$$Strg_{NH_3} = \int \frac{MG_{NH_3} \times [(MF_{urea} \times V_{urea} \times \rho_{urea}/MG_{urea} \times v) - ((DeNO_X + NH_{3,slip}) \times M_{exh}/MG_{exh} \times 10^3)]}{3600} \quad (2)$$

where V_{urea} is the urea dosage (ml/h); ρ_{urea} is the urea density (g/ml); M_{exh} is the exhaust mass flux (kg/h); $NO_{X,In}$ is the engine-out NO_X concentration (ppm); C_{max} is the maximal NO_X conversion efficiency (%); $DeNO_X$ is the amount of NO_X reduction (ppm); $NH_{3,slip}$ is the outlet NH_3 concentration (ppm); $Strg_{NH_3}$ is the current ammonia storage (g); NSR is the NH_3:NO_X ratio; MF_{urea} is the urea mass fraction in AdBlue (MF_{urea} = 0.325); MG_{urea}, MG_{NH_3} and MG_{exh} are the molar mass of urea, NH_3 and exhaust gas (g/mol) respectively and v is the stoichiometric coefficients of urea decomposition (v = 0.5).

A series of experiments were conducted at fixed engine operating conditions with different speed and temperature. Meanwhile, the interval for speed was 100 rpm and the interval for temperature was 25 °C. Then, the results under different temperatures and SV were obtained, as shown in Fig. 2.

In the experiment, the engine was running at a steady operating condition. The engine-out NO_X levels varied with different engine conditions and the urea was injected into the exhaust pipe with a fixed NSR. According to the required NO_X conversion efficiency, the NSR was set to 0.9. The injection ended when the NO_X concentration after catalyst achieved stability. Meanwhile, in this paper, the ammonia storage at this time is defined as the saturated ammonia storage whereas the time that the saturated ammonia storage is realized is defined as saturated time.

A criterion for the stability of outlet NO_X concentration is calculated by Eq. (3):

$$St = \frac{\int_{t-10}^{t} NO_{X,Out} - \int_{t-20}^{t-10} NO_{X,Out}}{\int_{t-20}^{t-10} NO_{X,Out}} \quad (3)$$

where St refers to the stability coefficient; t is time (s) and $NO_{X,Out}$ is the NO_X concentration after catalyst (ppm).

In this paper, the outlet NO_X concentration is considered as stable when the St is below 1%.

The characteristics of ammonia storage

Effect of exhaust temperature on ammonia storage process

The effect of exhaust temperature on the ammonia storage process was investigated when the SV was maintained at 1×10^4,

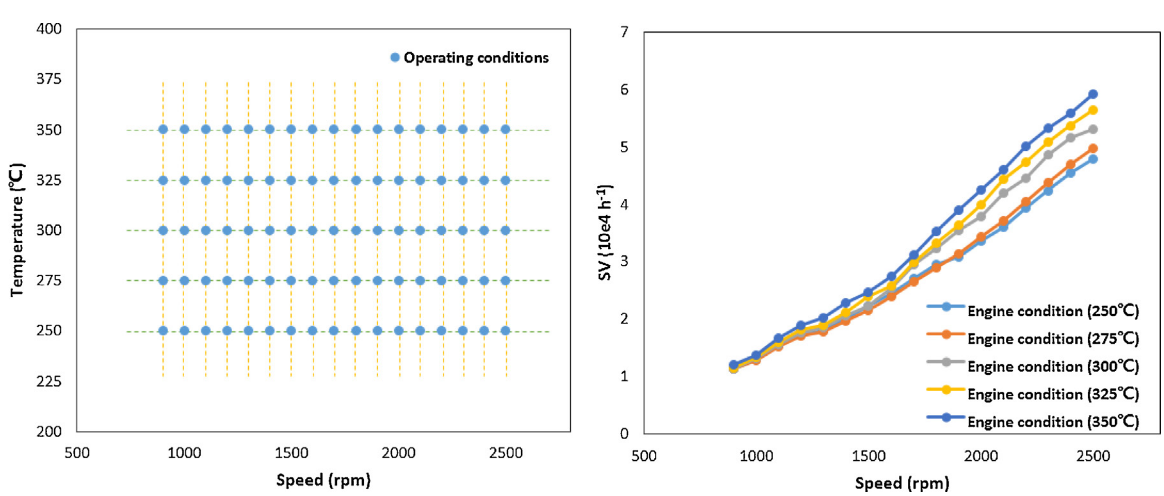

Fig. 2. Steady operating conditions.