# The Model Based Control Strategy for an Advanced UREA-SCR System

Zhi Liu, Hongrong Wang and Yongfu Wang

**Abstract** Currently the advanced UREA-SCR system is one of the most popular technology to meet the strict emission standards as Euro IV or above. In order to reach high NOx conversion and low $NH_3$ slip, the urea dosing rate needs to be calculated and controlled precisely. This paper describes an advanced UREA-SCR system based on model based control strategy and advanced diaphragm urea dosing pump. The strategy can be seen as a virtual closed-loop control method for the dosing rate calculation, and it was integrated with the advanced diaphragm urea dosing pump for the tailpipe urea dosing. A SCR chemical reaction model was developed to describe the concentration of different spices inside the SCR catalyst. Three different reactions were taken as the foundation of the model, including fast reaction, normal reaction and slow reaction. To simplify the process of calculation, the catalyst model was divided to three cells. In each cell, the $NH_3$ storage ability was estimated and the results were taken as the feedback signals for the controller. A virtual closed-loop control method was developed to calculate the dosing rate. The model was tuned under different engine running conditions, the exhaust gas temperature was controlled between 250 and 400 °C and the $NH_3$/NOx molar ratio was controlled between 0.8 and 1.1. An advanced-diaphragm urea dosing pump was developed to finish the urea dosing activity. The results of transient engine running experiment show that the NOx conversion efficiency can reach 85 % while keeping the average $NH_3$ slip under 15 ppm, the peak average $NH_3$ slip under 30 ppm. And the dosing rate error can be controlled less than 3 %.

**Keywords** Diesel engine · UREA-SCR · Model based control · NOx · SCR

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# 1 Introduction

As one of the main technology method to meet the Euro IV or more strict emission regulation, SCR technology has been widely used all over the world. Compared with another main technology-EGR, SCR has the advantage of simple structure, obvious effect to reduce NOx emission and has low fuel consumption. To control the dosing rate of UREA, the system needs to take the balance of NOx conversion efficiency and ammonia slip into account. That means if the system has a smaller UREA dosing rate than requested, the NOx conversion efficiency will be affected, and the ammonia slip will be reduced. And if the system has a larger UREA dosing rate than requested, though the NOx conversion efficiency can reach a higher level, the ammonia slip will exceed the standard. When the engine runs in a steady state, it is easy to adjust the dosing rate to balance the NOx conversion efficiency and ammonia slip. But when the engine runs in transient state, it is hard to reach the balance.

To control the ammonia slip, some catalyst companies are carrying out the research of clean-up catalyst. This kind of catalyst consists with reduction part and oxidation part. The reduction acts as a reduction catalyst to reduce the NOx, and the oxidation part acts as a oxidation catalyst to reduce the extra ammonia. Compared with other SCR catalyst, the clean-up catalyst may leads to larger UREA dosing rate and the cost will increase. And the OBD will have requirement on the diagnostic of the catalyst, which makes the SCR system more complex.

To consider the balance between the NOx conversion efficiency and ammonia slip, this article develops a SCR reaction model to estimate the chemical reaction and ammonia storage inside the catalyst. And the control strategy makes use of the ammonia storage as feedback to adjust the requested dosing rate. Unlike the black-box control strategy, the model based control strategy understands the chemical process inside the catalyst, thus it can predict what is going to happen of NOx conversion. The ammonia storage factor is estimated as a virtual sensor. To realize the high quality control, an advanced-diaphragm urea dosing pump was also developed to finish the urea dosing activity.

# 2 SCR Chemical Reaction Model

Inside the SCR catalyst, there are several different types of chemical reactions, including reduction reaction, oxidation reaction and ammonia adsorption and desorption.

**Fig. 1** Change of ammonia
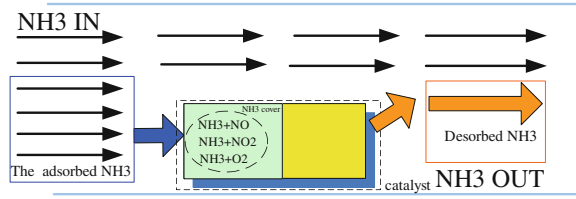


## 2.1 Ammonia Concentration Model

After the ammonia goes into the catalyst, there are two types of change inside catalyst.

The one is adsorption and desorption. From the upstream to the downstream of the catalyst, the ammonia is adsorbed to the surface of the catalyst. At the same time, the ammonia is released from the surface of the catalyst, this is called desorption. The adsorption and desorption are shown in Fig. 1.

The other one is chemical reaction. On the surface of SCR catalyst, because of the adsorbed ammonia, the activation energy decreases a lot. As a result, the ammonia reacts with NOx, and the NOx is converted to $N_2$ and $H_2O$.

According to the Law of conservation of mass, we can get the equation to describe the change of the ammonia mass [1].

$$\frac{\partial}{\partial t}[gas] = -v\frac{\partial[gas]}{\partial x} - r_{[gas]} \tag{1}$$

From the equation, we can know that the change of ammonia concentration consists of two parts, including the mass diffusion and the chemical reaction.

### 2.1.1 Adsorption and Desorption

We can describe the adsorption and desorption process with the equation as:

$$r_{[NH_3]} = r_{[a]} - r_{[d]} \tag{2}$$

The $r_{[a]}$ is the rate of ammonia adsorption, the $r_{[d]}$ is the rate of ammonia desorption. And the $r_{[a]}$ minus $r_{[d]}$ is the change of concentration of ammonia by the effect of adsorption and desorption.

The $r_{[a]}$ can be calculated as [1]:

$$r_{ads} = k_{ads}[NH_3](1 - \theta) \tag{3}$$
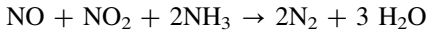
The $r_{[d]}$ can be calculated as [1]:

$$r_{des} = k_{des}\, e^{\frac{-E_{des}(1-\alpha\theta)}{RT}}\theta \tag{4}$$

The $k_{ads}$ is the reaction constant of the adsorption reaction. And the $k_{des}$ is the reaction constant of the desorption reaction. $\theta$ is the ammonia coverage rate of the catalyst surface .
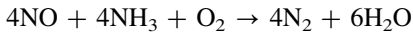
## 2.1.2 Chemical Reaction

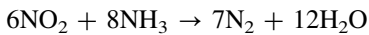There are three types of NOx reduction reactions listed as follows:

Fast reaction:

$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3 H_2O$

Normal reaction:

$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$

Slow reaction:

$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$

We can describe the reduction reaction rate as:

$$r_{NO_x} = k_{NO_x}\, e^{\frac{-E_{NOx}}{RT}} [NO_x]\theta \tag{5}$$

The $k_{NO_x}$ represents the reduction reaction constant, the $E_{NOx}$ represents the reaction activation energy, the $[NO_x]$ represents the concentration of the NOx and $\theta$ is the ammonia coverage rate of the catalyst surface.

From the Eq. (1)–(5), we can know that four parts contribute to the change of the ammonia surface coverage, the ammonia adsorption rate, the ammonia desorption rate, the NOx reduction reaction rate and the ammonia oxidation rate.

With the four different reaction equations, we can build the model of the reactions inside the catalyst and to describe the ammonia surface coverage.

## 3 Reaction Model Calibration

Once we get the model of the chemical reaction rate inside the catalyst, we need to calibrate the parameters of the calibration. The parameters are listed as follows [2]:

| | |
|---|---|
| $k_{ads}$ | reaction constant of the adsorption reaction |
| $k_{des}$ | reaction constant of the desorption reaction |
| $E_{des}$ | reaction activation energy of the desorption |
| $\alpha$ | surface coverage dependence for desorption |
| $E_{NOx}$ | reaction activation energy |
| $k_{NO_x}$ | NOx reduction reaction constant |

And the input of the model includes NOx concentration, ammonia concentration, the flow mass of exhaust gas and the temperature in the upstream of catalyst.

To simplify the calculation process of the reaction inside the catalyst, the catalyst is divided into three cells, we assume that inside each cell, the concentration of NOx and ammonia, the temperature are the same in every point. As
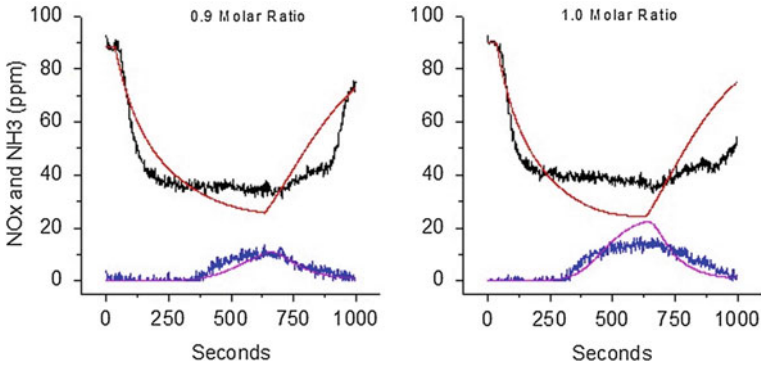
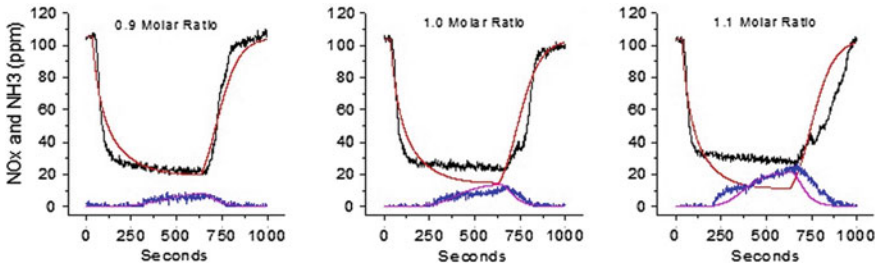**Fig. 2** 225 °C, tuning result



**Fig. 3** 250 °C, tuning result

showed in the picture, we build the three ammonia coverage virtual sensor to estimate the ammonia coverage.

To calibrate the six parameters, different calibration experiments are designed. The ammonia NOx ratio varies from 0.9 to 1.1, and the temperature in the upstream of the catalyst varies from 225 to 400 °C. The compare between the testing result and the model calculation are showed as follows (Figs. 2, 3, 4 and 5).

Testing condition: 225 °C, molor ratio from 0.9 to 1.0.

Testing condition: 250 °C, molor ratio from 0.9 to 1.1.

Testing condition: 350 °C, molor ratio from 0.9 to 1.1.

Testing condition: 400 °C, molor ratio from 0.8 to 0.9.

After we got the data, we make use of the Mathwork toolbox to fit the model, and get the best result.

# 4 Model Based Control

The model based control strategy makes use of the model to estimate the NOx conversion efficiency and the catalyst surface coverage [3].
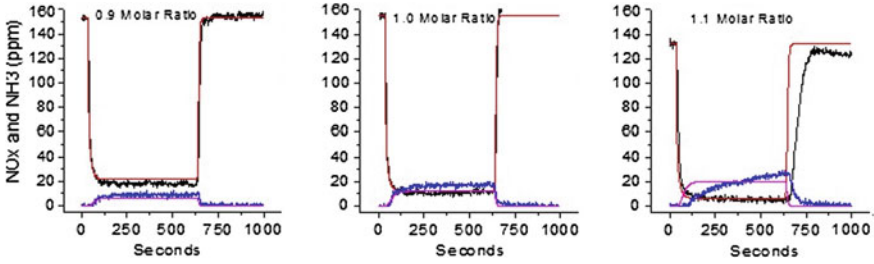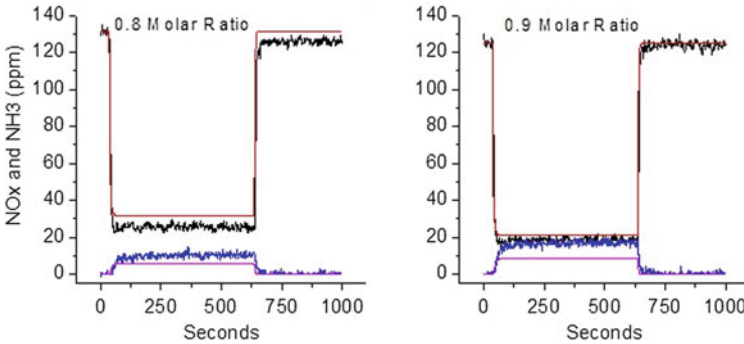
**Fig. 4** 350 °C, tuning result



**Fig. 5** 400 °C, tuning result

The strategy includes two parts: the UREA dosing calculation and the NOx conversion efficiency calculation. The UREA dosing calculation make use of the engine exhaust mass, NOx exhaust concentration and the temperature in the upstream of the catalyst as the input, to calculate the requested UREA dosing rate. The NOx conversion efficiency calculation makes use of the model to calculate NOx conversion efficiency.
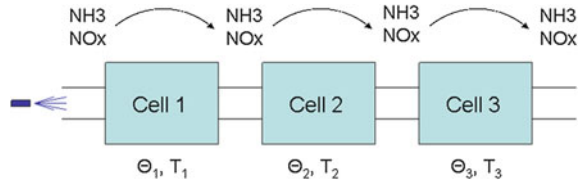
## 4.1 Urea Dosing Calculation

The UREA dosing calculation includes two different modular.

### 4.1.1 Thermal Model

The goal of the thermal model is to predict the temperature inside the SCR catalyst and the Diesel Particulate Filter. The exhaust flow mass and temperature will be used as the input values.

**Fig. 6** Three cells



### 4.1.2 PID Controller

The UREA dosing rate is controlled by a PID controller. The catalyst is divided into three parts. We assume that inside every cell, the condition is exactly the same in every point (Fig. 6).

The theta from cell3 is used as feedback. The goal of the controller is to keep the model calculated theta within the requested level. The controller is a typical PID controller, includes open controller, proportional controller, integration controller and derivation controller.

## 5 UREA Dosing System

An advanced UREA dosing pump was developed to carry out the activity of UREA dosing. The pump includes two modules, the pump and the control system.

### 5.1 Pump

The pump inhales the UREA from the UREA container, and by the use of motor, the UREA is imported into the pump at the pressure about 2–3 bar. The UREA dosing pump receives the command from dosing rate calculation module, and doses the requested amount of UREA into the exhaust pipe. The dosing pump has the air assistant system to help the UREA hydrolyze to ammonia. The flow pressure is built by the drive of diaphragm pump which is drived by the motor. The dosing pump can carry out the dosing rate accurately, and when the environment temperature under 5 °C, the heater can start to heat up the dosing pump.

### 5.2 Control System

The control system can control the work of the pump. It includes MCU module, the DC/DC module, the signal process module, the actuator drive module and the CAN-BUS communication module. Those modules are integrated together and installed with the pump.
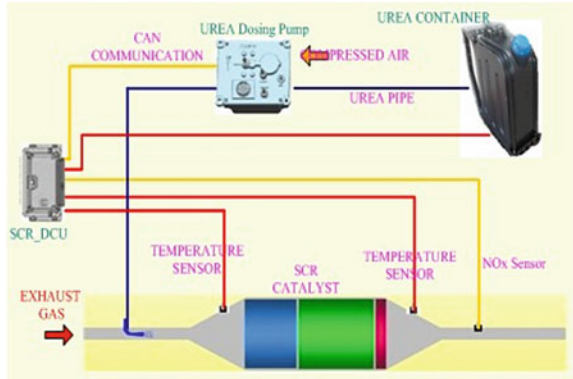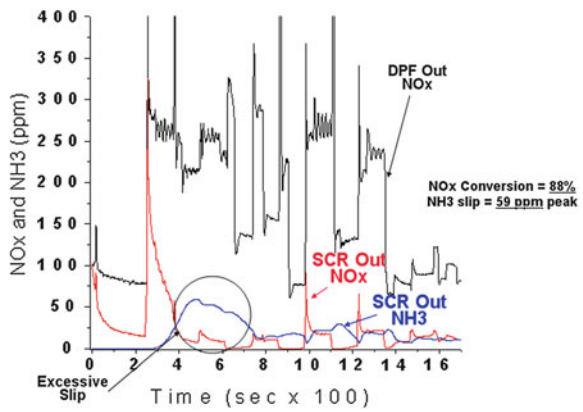
**Fig. 7** Test platform



**Fig. 8** ESC test result



## 6 Experiment

Several different types of experiments are carried out to verify the performance of the control strategy.

### 6.1 Test Platform Configuration

The test platform are consists of SCR catalyst, temperature sensor, UREA Dosing Pump and DCU. The configuration are showed in Fig. 7.

As shown in the Fig. 7, the UREA Dosing Pump and SCR_DCU are developed by CAERI. We integrate every part into the SCR system. The selected engine's volume is 12.8 L, and the max power is 480 Hp.
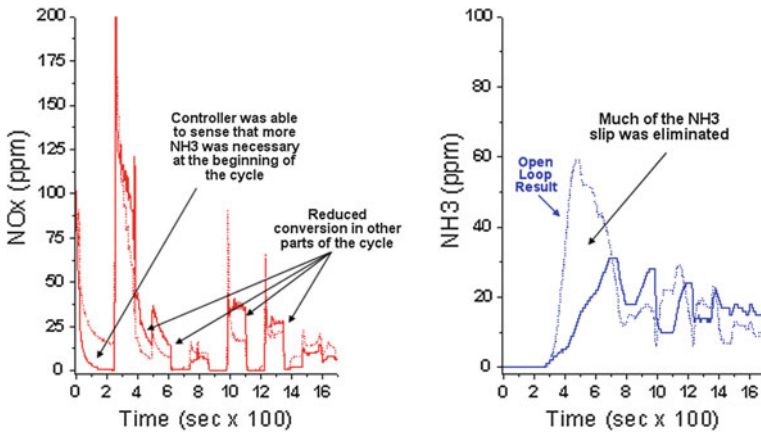
**Fig. 9** ESC test result

## 6.2 Test

Because the UREA system are almost used in the heavy duty truck, so the ESC cycle is selected to run steady state condition, and the FTP cycle is selected to carry out the experiments [4].

### 6.2.1 ESC Result

The open loop control strategy and closed-loop strategy are both verified in the ESC result and parts of the results are shown in the following figures (Fig. 8).

From the ESC condition open-loop experiment, we can see that the NOx conversion is closed to 90 %, but the $NH_3$ slip seems too high (Fig. 9).

From the ESC condition closed-loop control, we can see that the $NH_3$ slip decreases a lot because of the feedback of the coverage of the ammonia on the surface of catalyst.

### 6.2.2 FTP Tests

The FTP tests are consists of four parts, the NYNF, LANF, LAFY, NYNF. The results of the FTP cycle are shown as follows (Fig. 10).

We can see that compared with the open-loop control strategy, the closed-loop control strategy can decrease the ammonia slip while keeping the NOx conversion efficiency seems as the same as open-loop control, that means the efficiency is closed to 90 %.
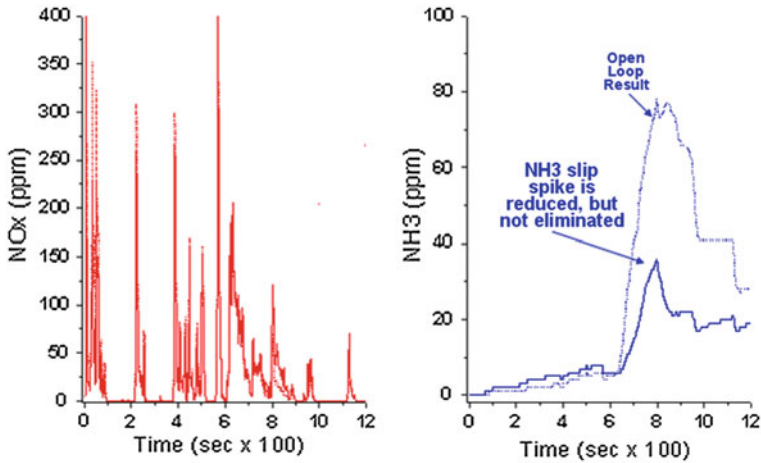
**Fig. 10** FTP test result

## 7 Conclusion

An advanced SCR system was introduced in this paper, including model based control strategy and advanced urea dosing pump. The experiments showed that this advanced system can have a high $NH_3$ conversion efficiency (closed to 90 %) while keeping a low $NH_3$ slip. The max $NH_3$ slip is about 30 ppm and the average $NH_3$ slip is less than 10 ppm. And the dosing rate error can be controlled in a very low level.

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