EXPERIMENTAL STUDY ON THE UREA SCR SYSTEM FOR MEDIUM DUTY TRUCK

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Abstract

The urea SCR system is one of the promising techniques to reduce nitrogen oxide (NOx) in the exhaust gas without fuel penalty. Its application, however, seems to be a complex task because it requires to keep the ammonia slip (NH_3 slip) to a minimum level. In practice, controlling the NH_3 slip is not easy because 1) the exhaust gas temperature varies significantly from low to high levels, and 2) the operational conditions change rapidly. In this research the catalyst performance was tested in order to investigate these two points. First, under steady state conditions we studied the effect of the load and urea-equivalence ratio on NOx emissions and NH_3 slip, and verified the applicable temperature range of the urea SCR system. Secondly, under the rapid changes of the operating conditions we studied the urea SCR system's response and robustness for a better understanding of the urea injection control strategy.

1. Experimental setup and approach

As shown in Fig. 1, the urea SCR system was composed of a pre-oxidation catalyst block (1-2), three blocks of SCR catalysts (3-6), and a post-oxidation catalyst block (6-7). The urea-solution was injected immediately after the pre-oxidation catalyst. A gasoline direct injection engine injector was used to supply the urea-solution intermittently, changing the inputting square pulse width.

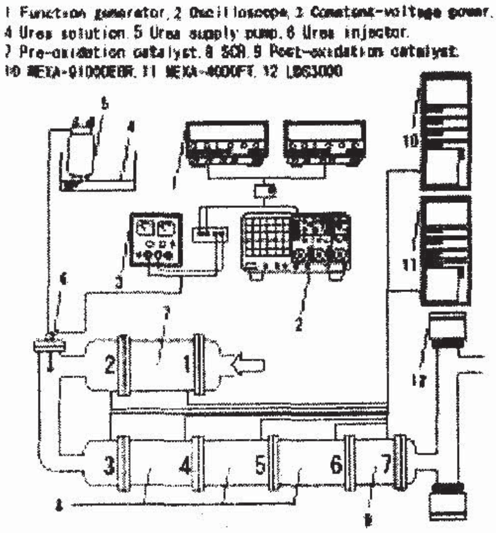

Fig. 1. Experimental setup

The duty ratio of inputted square pulse was varied to control the injection amount based on the previously examined mapping. To determine the injection amount of the urea-solution, the 'Urea-equivalence ratio' or 'ϕ_{urea}' was defined as the ratio of the injection amount to the stoichiometric amount, given by the following formulas (1) and (2), which describe the total reduction of NOx into N_2.

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \tag{1}$$

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 6H_2O \tag{2}$$

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O \tag{3}$$

$$\phi_{urea} = \frac{N_0}{N_{th}} \tag{4}$$

where N_0 is the injected NH_3 and N_{th} is the NH_3 theoretically required. Seven sampling points were placed on the exhaust gas flow as shown in Fig. 1, allowing to investigate the characteristics of each catalyst by measuring the catalyst temperatures and emissions. Exhaust gas analyzers, HORIBA MEXA-9100DEGR, MEXA-4000FT, and SIEMENS LDS3000 were used.

2. Experimental conditions

The experimental conditions are listed in Table 1. The experiments were carried out at a 60% of the maximum engine speed, 1440 rpm, and the load and ϕ_{urea} were used as the parameters. Firstly, the NOx reduction characteristics of the urea SCR system, were tested under steady state conditions with constant load and ϕ_{urea} (1. Steady state). Next, we investigated the urea SCR system's response and robustness by inputting a step changed ϕ_{urea} under constant load condition (2. Urea injection). Furthermore, under rapid changes of operating conditions (3. Transient state), we studied the urea injection control strategy by comparing the NOx emission and the NH_3 slip trends with the varied ϕ_{urea}. In tests 2 and 3 in Table 1, (1.0, 40), for example indicates that the urea-solution at $\phi_{urea}=1.0$ is supplied to NOx emission produced at the 40% load operational condition. The latter two blocks of the SCR catalysts and the post-oxidation catalyst were removed for Test 1 at 10% load and for all loads in Tests 2 and 3 to quicken the response of catalyst temperature by lowering these heat capacities.

Table 1. Experimental conditions

Test	Engine speed rpm	Load %	ϕ_{urea} or (ϕ_{urea}, Load)	Catalyst configuration
1. Steady state	1440	80	0.8, 1.0, 1.2	pre-oxidation catalyst +3 SCR catalysts +post-oxidation catalyst
		20	0.8, 1.0, 1.2	
		10	1.4	pre-oxidation catalyst +1 SCR catalyst
2. Urea step injection	1440	40	(0, 40)→(1.0, 40)	
			(1.0, 40)→(0, 40)	
		80	(0, 80)→(1.0, 80)	
			(1.0, 80)→(0, 80)	
3. Transient state	1440	40→80	(1.0, 40)→(1.0, 80)	
			(1.0, 40)→(0, 80)	
			(1.0, 40)→(0.6, 80)	
		80→40	(1.0, 80)→(1.0, 40)	
			(1.0, 80)→(1.6, 40)	

3. Results and discussion

3. 1. Steady state

The exhaust gas temperatures and emissions at each sampling point under steady state conditions are shown in Fig. 2 and 3 respectively.

80% Load

The NOx reduction rate was very high due to the high activation of the SCR catalysts caused by the high exhaust gas temperature (Fig. 3(a)). However, the majority of the residual NH_3, which was considered to convert to NOx by the action of the post-oxidation catalyst, deteriorated the NOx reduction rate at the sampling point 7. For that reason the recommended ϕ_{urea} is below 1.0 at this condition.

20% Load

There were almost no differences in NO and NO_2 concentrations between the sampling points 1 and 2, which are the inlet and outlet of the pre-oxidation catalyst block, because of the low exhaust gas temperature at this load (Fig. 3(b)). For the same reason, the activation of the SCR catalysts was low, resulting in a low NOx reduction rate. Therefore NH_3 slip at the exit of each SCR catalyst block (at the sampling points 4,5, and 6) was large. No improvement of the NH_3 slip was achieved between the inlet and outlet of the post-oxidation catalyst block. Consequently, it can be said that, at this load, a ϕ_{urea} value below 1.0 is recommendable. It also indicates that the concentration at the sampling point 4 exceeded that at the sampling point 3. This was because the decomposition of the urea-solution was not complete and the production of NH_3 occurred at the surface of the SCR catalyst. NO_2 almost achieved a complete reduction compared to NO, as NO_2 concentration was lower than NO concentration at the sampling point 3. Judging from this result, it is suggested that the reaction at a NO/NO_2 ratio=1.0 is dominant in the NOx reduction reactions.

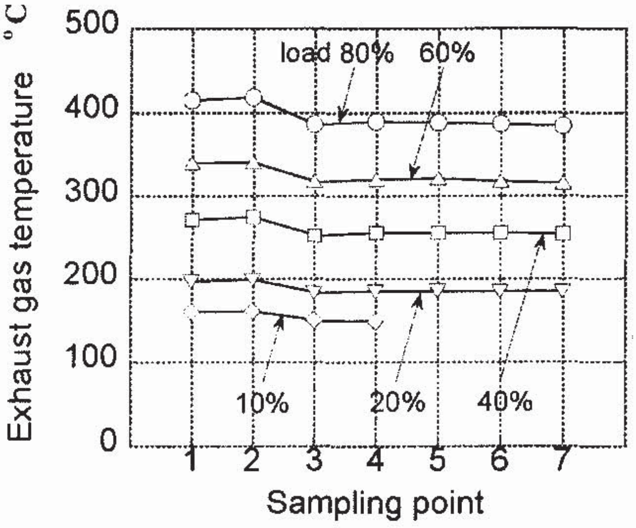

Fig. 2. Exhaust gas temperature ateach sampling point

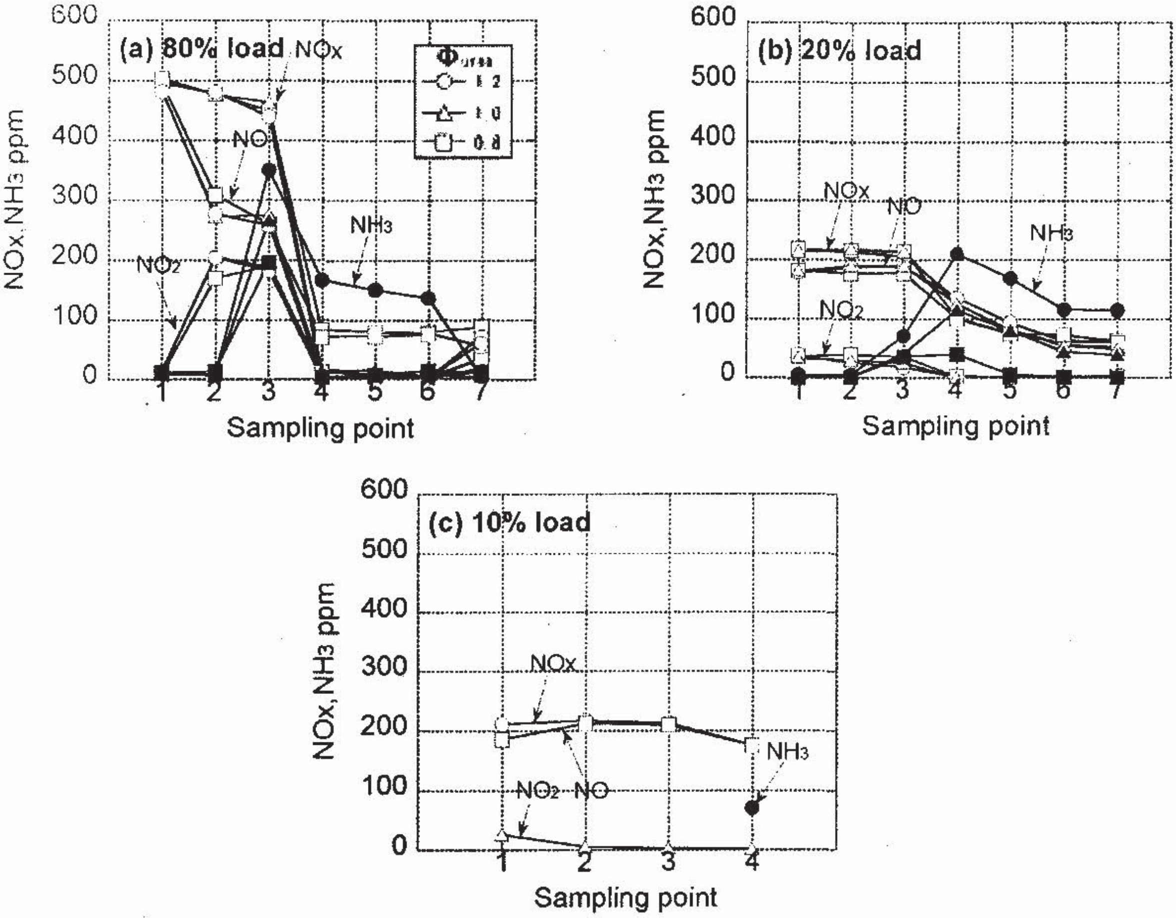

Fig. 3. NOx and NH3 emissions at each sampling point under steady state conditions

10% Load

The concentrations of NO and NO_2 shown in Fig. 3(c) indicate that no oxidation of NO by the action of the pre-oxidation catalyst occurred at this temperature. The NOx reduction rate was very low due to the low activation of the SCR catalysts. It is suggested from the results of the steady state engine tests that the NOx reduction rate under the transient condition would be worse than those under the steady state condition. Furthermore a great deal of NH_3 slip will occur if the urea injection quantity increases rapidly according to the SCR catalyst temperature because the adsorption capacity of NH_3 on the SCR catalysts is higher at lower temperatures. Therefore further study will be required for the injection control strategy under these operating conditions.

3. 2. Urea step injection

40% Load

Fig. 4(a) shows NOx, NO and NH_3 concentrations at the exit of the SCR catalyst block when the step changed ϕ_{urea} was supplied to the urea SCR system under the 40% load operating condition. Timescale was set to 0 at the start of urea-solution injection. Between NOx and NH_3 concentrations, NOx concentration decreased rapidly in the early stage, and then froze. On the other hand, NH_3 concentration increased gradually. This is because NH_3 adsorption tends to take place as soon as the urea injection is started.

Fig. 4(b) shows the record of NOx, NO, and NH_3 concentrations when the urea injection was cut off. NH_3 concentration decreased to zero at about 100 sec, while NOx and NO concentrations increased. This was because the adsorbed NH_3 was consumed with time. The comparison of Fig. 4(a) and 4(b) indicates that the time each chemical specie required to reach a plateau was longer for the former one.

80% Load

Fig. 5(a) and 5(b) show the results at 80% load. Comparison with the results at 40% load shows similar trends. It can be observed that the time to reach a plateau is shorter compared to the 40% load condition. This is because the catalyst temperature at 80% load was higher and the amount of NH_3 adsorbed was smaller. Fig. 5(b) indicates the record of NOx, NO and NH_3 after cutting off the urea injection. As shown in this figure, the NOx reduction effect was kept for a while, even after the NH_3 slip stopped, reproducing the same tendency of the 40% load condition.

Judging from these results, the NH_3 slip depends on the amount of NH_3 adsorbed on the surface of the SCR catalyst, which must be considered in order to reduce NOx emissions effectively with a minimum urea injection.

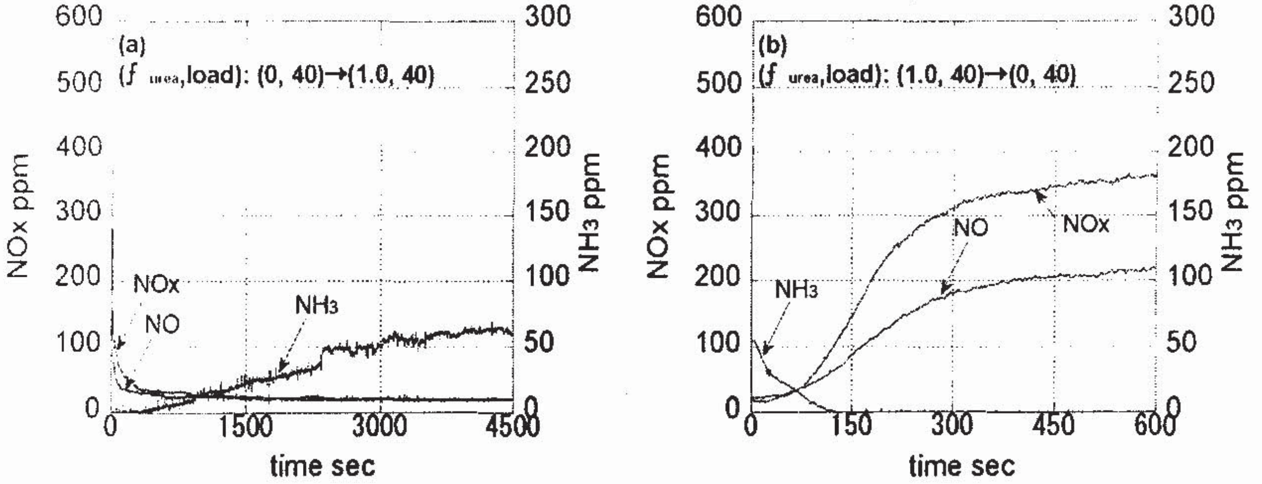

Fig. 4. NOx and NH3 emissions at the exit of the SCR catalyst block (40% load)

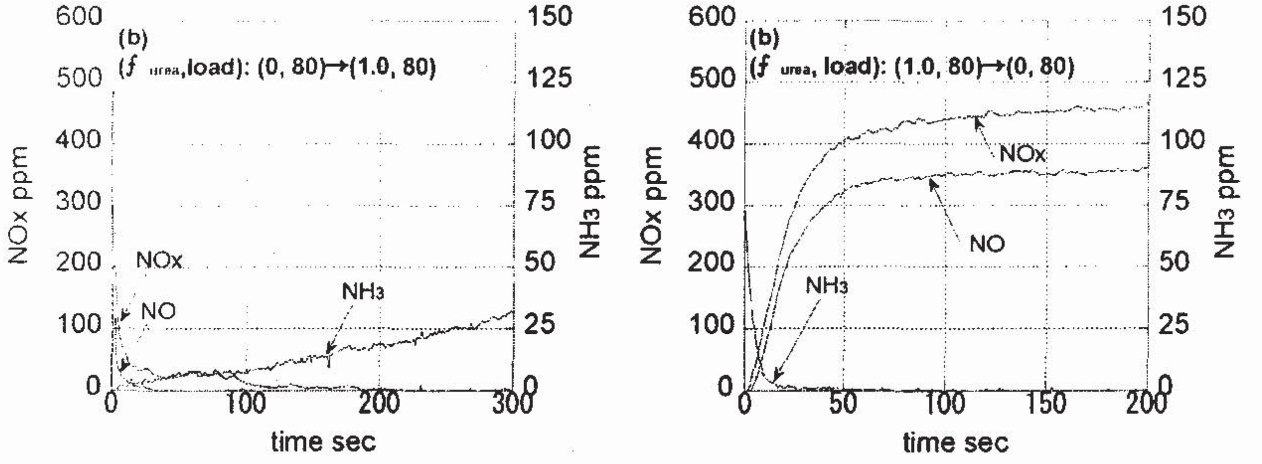

Fig. 5. NOx and NH3 emissions at the exit of the SCR catalyst block (80% load)

3. 3. Transient state

40→80% Load

Fig. 6 shows the progress of the exhaust gas temperature while the load was step changed from 40 to 80%, and Fig. 7 shows the NOx and NH_3 concentrations at the exit of the SCR catalyst block. When (ϕ_{urea}, load) was changed from (1.0, 40) to (1.0, 80), as shown in Fig. 7(a), a high level of NH_3 slip was observed. This is due to the desorption of the NH_3 trapped on the surface of the SCR catalyst. NOx concentration increased once and then decreased. This result can be understood as the NOx concentration in the exhaust gas responds quickly to the change in load, while the catalyst temperature response is slower. Thus, a high activation cannot be achieved at the early stage. However, at the later stage, the SCR catalyst temperature reached a high level enough to lower the NOx concentrations.

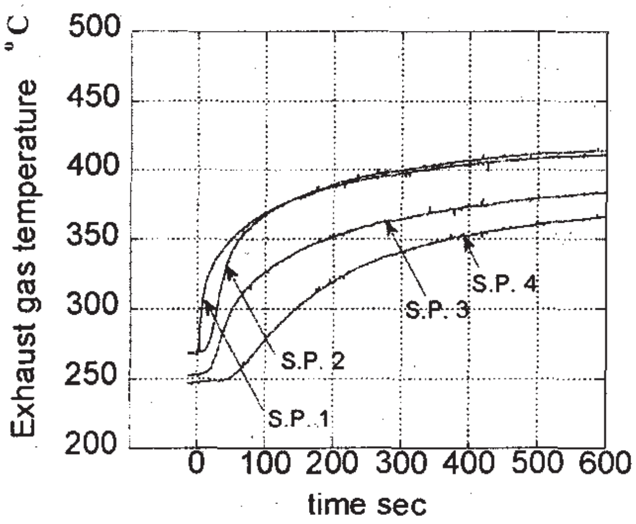

Fig. 6. Exhaust gas temperature at each sampling point (40→80% load)

Because of the high level of NH_3 slip measured when (ϕ_{urea}, load) was changed from (1.0, 40) to (1.0, 80), we inferred that a large amount of NH_3 was adsorbed on the surface of the SCR catalyst. Moreover the test was conducted by cutting off the urea injection at the time of load change. The result is shown in Fig. 7(b). In this case, no large NH_3 slip was measured, however a rapid NOx concentration increase was observed after about 50 sec. Comparison of the cases, (1.0, 40)→(1.0, 80) and (1.0, 40)→(0, 80), shows that NOx concentrations have similar trends until about 15 sec. This is because it requires 15 sec to increase the temperature of the SCR catalyst as shown in Fig. 6. Furthermore the NOx concentration was not affected by the supply of the urea-solution during the initial 15 sec, thus the injection control strategy should focus on the NH_3 slip and NOx emission after 15 sec.

The test was also conducted by supplying the urea-solution constantly in order to avoid the rapid increase of NOx emission after about 50 sec. The result is shown in Fig. 7(c). It shows that the rapid increase in NOx emission after 50 sec could be reduced, however the NH_3 slip became prominent again. And, as shown in Fig. 6, rise of temperature at the sampling point 4 started about 50 sec. Previously the rise of temperature at the sampling point 3 started at 15 sec, and we could estimate that the NH_3 desorbed upstream of the SCR catalyst was adsorbed again downstream.

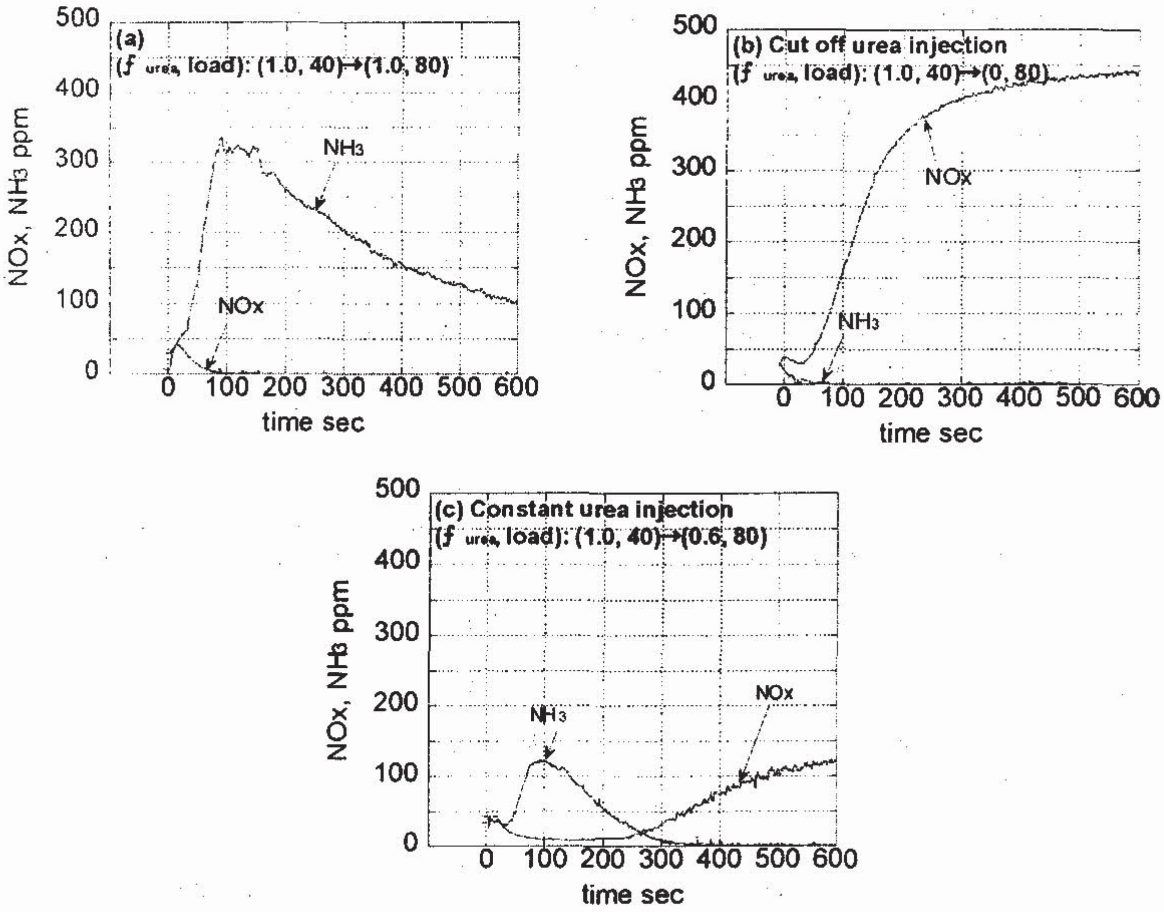

Fig. 7. NOx and NH3 emissions at the exit of the SCR catalyst block (40→80% load)

Load 80→40%

The results are shown in Fig. 8 and 9. At (1.0, 80)→(1.0, 40) (Fig. 9(a)), the NH_3 slip decreased until about 70 sec. This is because the supplied urea-solution amount decreased at the time of load change, along with the decrease of the SCR catalyst temperature. Then the NH_3 slip record shows an increase because the amount of NH_3 adsorbed on the surface of the SCR catalyst increased. NOx concentration was low up to about 50 sec. After that, it increased temporarily and then decreased because the reaction rate decreased in the early stage and later the adsorption of NH_3 increased.

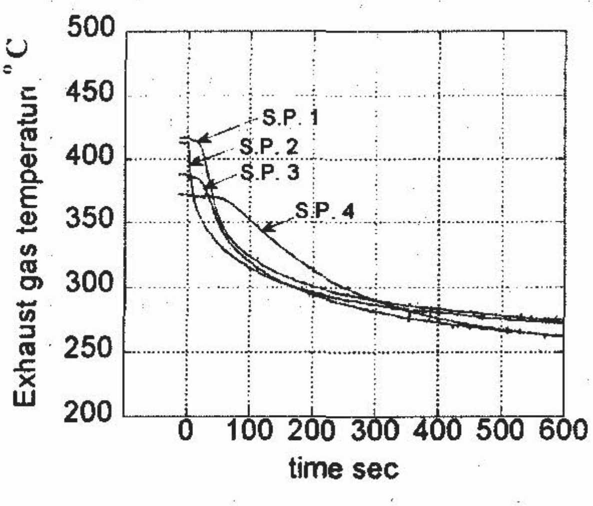

Fig. 8. Exhaust gas temperature at each sampling point (80→40% load)

With the aim of promoting NH_3 adsorption, the test was conducted under constant urea-solution injection rate. The result is shown in Fig. 9(b). The NH_3 slip increased shortly after the change of load because NOx emissions decreased at the time of load change. NH_3 slip decreased as NH_3 adsorption increased. Then, NH_3 slip decreased temporarily as the SCR catalyst temperature decreased. However, NH_3 slip increased rapidly due to the excessive supply of urea-solution. When these two results are compared, (1.0, 80)→(1.6, 40) condition showed a lower NOx concentration up to about 240 sec. However, NH_3 slip at this condition was considerably large, thus indicating that an injection method like this is not advisable. (1.0, 80)→(1.6, 40) condition showed a higher NOx concentration at 600 sec than that at (1.0, 80)→(1.0, 40) condition, showing that the excessive supply of urea-solution decrease the NOx reduction rate.

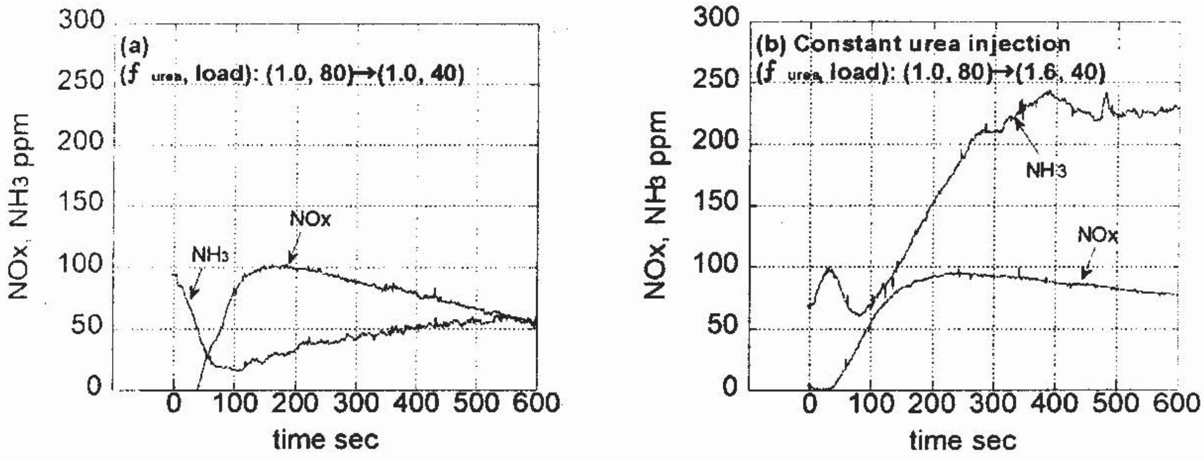

Fig. 9. NOx and NH3 emissions at the exit of the SCR catalyst block (80→40% load)

4. Conclusions

The urea SCR system was tested under steady and transient conditions for a medium duty truck. The following conclusions were drawn.

1. The reaction:

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

is dominant in the NOx reduction reaction process of the urea SCR system. Consequently, an improvement of the NOx reduction rate can be achieved by controlling the ratio of NO/NO_2.

2. The NH_3 slip associated with the change of the operating conditions can be avoided by controlling the urea-solution supply rate appropriately. For example, a temporal stop of the supply is effective during the transition process from low to high loads because the NH_3 trapped in the catalyst can be utilized.
3. It is important to pay close attention to the catalytic temperature and the amount of NH_3 adsorption when controlling the urea-solution supply. This is because the NH_3 slip under the transient condition depends on the change in the catalytic temperature, and thus on the amount of NH_3 adsorbed.

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