20056053

51 Development of NOx Storage Reduction (NSR) System for a DME Engine

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To establish NOx Storage Reduction(NSR) system, the effect of post fuel injection in exhaust pipe with rich spike on NOx conversion rate was investigated. With post fuel injection, a higher injection pressure and the rich spike close to the NSR catalyst (just before the NSR catalyst) shows better NOx reduction performance. Based on these results, exhaust emission was tested in transient driving mode (JE-05). In this driving mode test, it was possible to reduce NOx emission less than 0.5 g/kWh for only a 1% of fuel penalty controlling the rich spike injection precisely.

***Keywords* :** DME(Dimethyl Ether), NSR(NOx Storage Reduction) catalyst

1. INTRODUCTION

Along with high thermal efficiency, diesel engines are useful internal combustion engines for energy conservation and CO_2 reduction. Particulate matters (PM) and NOx, however, in the diesel emissions cause air pollution, especially in cities. For these reasons, DME(Dimethyl ether) fuel has been attracting attention as a alternative fuel in terms of diesel fuel (1).

DME has a high cetane number and compression ignition capability. This enables a high thermal efficiency comparable to diesel engines. Moreover, DME creates no smoke or sulfur oxide. As for NOx, however, even when using DME, there still remain problems under stringent exhaust gas regulations. To reduce NOx emissions in DME engines, a high EGR is effective, but for substantial NOx reduction, aftertreatment is needed.

For some time, lean NOx catalyst systems with continuous HC injection into the exhaust have been considered for diesel NOx reduction, but high fuel consumption penalty and low NOx reduction potential remain significant drawbacks. In recent years, the NOx Storage Reduction system, NSR, has attracted increasing interest due to the potential for increased NOx reduction performance and reduced fuel consumption. Therefore, a NSR catalyst was used as an aftertreatment device in a 7L heavy-duty DME(Dimethyl ether) engine with modified fuel supply system.

Key parameters such as pressure and position of rich spike which influence the NSR performance were investigated. Also, the effects of injection pattern on mixture formation in the catalyst and pipe were analyzed using a CFD code.

Especially, control of rich spike on transient driving mode test is one focus of this paper because DME fuel is used as NOx reducing agent. The strategy of this study is to obtain the high NOx reduction performance with minimizing the fuel penalty using the NSR system.

2. Mechanism of NSR catalyst

The mechanism of NSR catalysts is such that the exhausted NOx under lean conditions is stored on the catalyst surface. When it reaches in saturation condition during this normal operating condition, rich spike is added to exhaust stream. Then, stored NOx is released and reduced under net rich conditions. Gasoline engines can easily achieve rich combustion and also form large amounts of CO and H_2. These are very effective in NOx reduction. (2).

3. EXPERIMENTAL SETUP

3.1. DME engine

In the experiment, 6 cylinder diesel engine of 6.925 liters displacement (Table 1) was used. The combustion chamber is a toroidal one with an 18:1 compression ratio. The experimental system comprises a fuel injection system, a cooled EGR system, and an NSR system as shown in Fig.1 and 2.

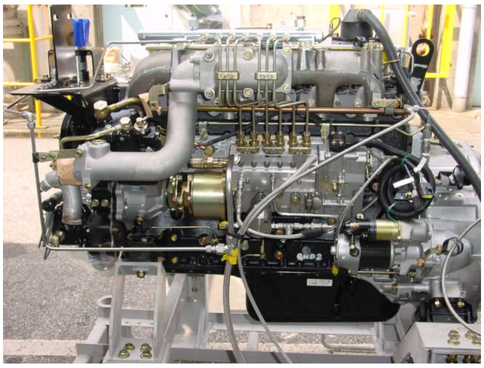


Fig.1 DME Engine

Table 1 Engine Specifications

	DME engine	Diesel engine
Type	4-stroke, 6 cylinder Turbo, Intercooler	←
Bore & Stroke mm	108×126	←
Displacement L	6.925	←
Compression ratio	18.1	←
Injector hole mm	0.5 dia.×5 holes	0.2dia.×5 holes
Target performance	199kW/2700 rpm 716Nm, /1400 rpm	←

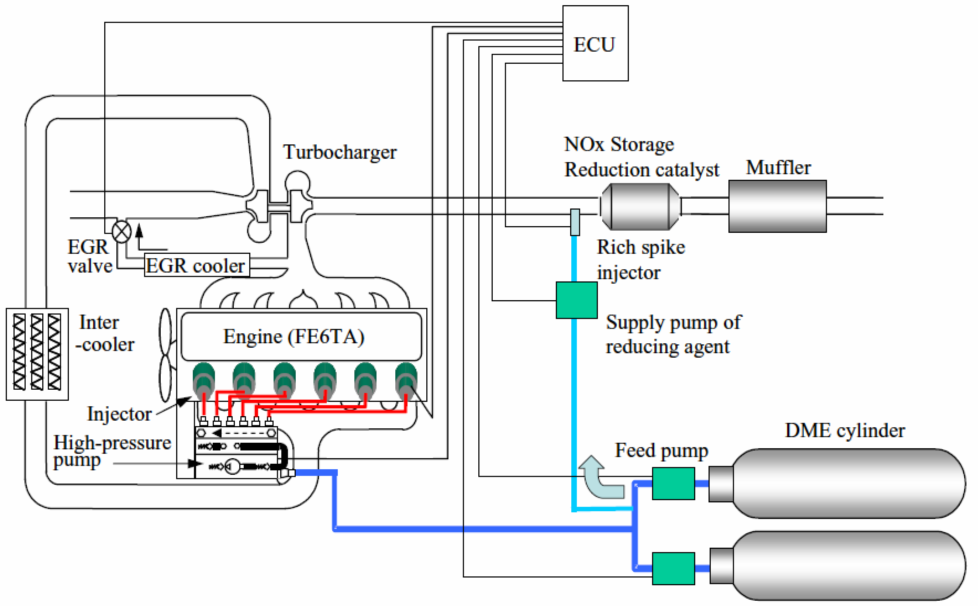


Fig.2 Experimental apparatus

3.2. NSR Catalyst

Table 2 shows the specifications of catalyst used for the experiment. This Pt/Rh type catalyst is selected from the single cylinder engine test(2), and Figure 3 show the reduction performance. This catalyst shows higher NOx reduction performance comparing other catalyst. It has a volume of 8.0 liters in consideration of heavy-duty engine displacement. As shown in Figure 4, the NSR system used for the engine experiment is equipped with an injector for adding the fuel-rich condition; a controller for the rich spike; and a computer with interfaces for displaying and storing data. This NSR catalyst is located in the place of 1.4m from the turbocharger. And effect of injector location on NOx reduction performance is tested. Rich spike injector is installed in the place of 15cm and 25cm from catalyst and turbocharger respectively as shown in Figure 4. A zirconium （ZrO_2） wide range oxygen sensor was used to measure the air-to-fuel ratio (A/F ratio). And also gas analyzer with NDIR, CLD, and HFID analytical apparatuses are used to measure CO, NOx, and THC respectively. Injector with an electromagnetically driven direct-lifting needle valve (single holeϕ 1.0mm) was used for rich spike. Fuel injection pressure for R/S is limited to 12 MPa considering the structure and strength of the injector. Fuel injection duration is variable according to the engine operation condition.

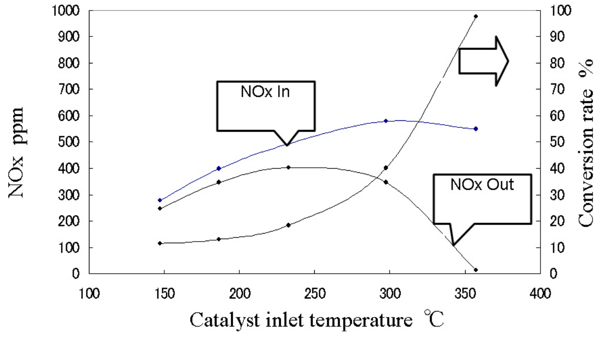


Fig.3 Characteristic of NSR catalyst

Table 2 Catalysts specifications

Component & Size	Characteristics
Pt / Rh 144×152 (dia.×L)	-Low temperature activity -Improvement of NOx reaction

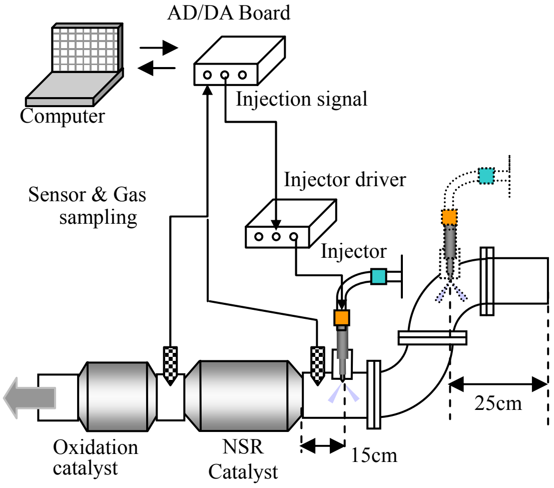


Fig.4 NSR System

3.3. Experimental method

The experiment began with an engine test to obtain effective NOx reduction performance under steady state operating conditions. Effects of rich spike position (Figure 4) and injection pressure on NOx reduction were investigated. The engine was operated with constant engine speed of 1080 rpm and 80% load. The NSR system is constructed on the basis of these results.

Then, using this NSR system which shows high performance, the control algorithm of rich spike injection is programmed and evaluated under transient driving mode test (JE-05). Figure 5 shows the driving pattern of JE-05. This mode is scheduled to replace D-13 conventional mode test in 2005 year.

In transient driving mode test, performance and emission test were carried out in the order of base condition, EGR control and rich spike control in NSR system as shown in Table 3. In rich spike control test, control is optimized as the control advances to 6 from the control 1.

In the rich spike control test, DME fuel is used as the NOx reducing agent in the intermittent spraying for the NSR catalyst, but it may lead to negative effects on fuel economy. Therefore, it is necessary to minimize the rich spike while maximally reducing NOx. A flow chart summarizing the algorithm is shown in Figure 6. The key point of the algorithm is to obtain a high NOx reduction performance while minimizing the fuel penalty.

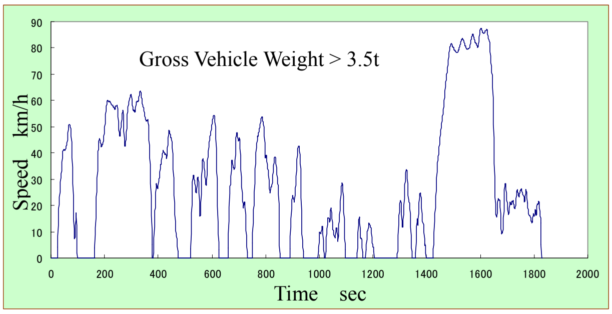


Fig.5 JE-05 mode for transient driving test

Table 3 Experiment flow

Base	Base engine condition
EGR	Exghaust Gas Recirculation control
Rich spike control	
Control 1	R/S injection is applied in regular interval and quantity
2	Optimization in the R/S injection interval
3	Optimization in the R/S injection quantity
4	Precision of R/S interval and quantity
5	Installation of intake throttle and thermal insulation in exhaust system
6	Optimization of catalyst volume (8L NSR catalyst + 4L NSR catalyst)

For controlling the rich spikes for the NSR catalyst, key data were gathered from the engine (engine speed and load) and from the catalyst (catalyst temperature and NOx concentration). After these data were fed into a computer, the advisability of rich spikes was evaluated. If the conditions for regeneration of the NSR catalyst are satisfied, the algorithm controls the amount and timing of the DME fuel injection in accordance with the conditions of the engine and the catalyst. After conducting the transient driving test, the effects of rich spike control on fuel economy, NOx, and NMHC was evaluated. The algorithm was optimized by repeating the setting and adjustment of program.

3.4. Numerical analysis

The air motion can be described by the principle of the conservation of mass and momentum. In order to analyze the characteristics of turbulent airflow motion, a time-averaged Reynolds equation and turbulence model are applied. In addition, turbulent diffusion model should be considered to analyze the mixing of fresh-air and burned gas that occupies the cylinder at the end of exhaust stroke. In this study, the commercial software FLUENT 6.2 is used to perform the transient analysis of airflow motion and diffusion. The governing equations applied to FLUENT$^{(7)}$ are summarized as follows.

- Continuity equation

$$\frac{\partial(\rho U_i)}{\partial x_i} = 0 \qquad (1)$$

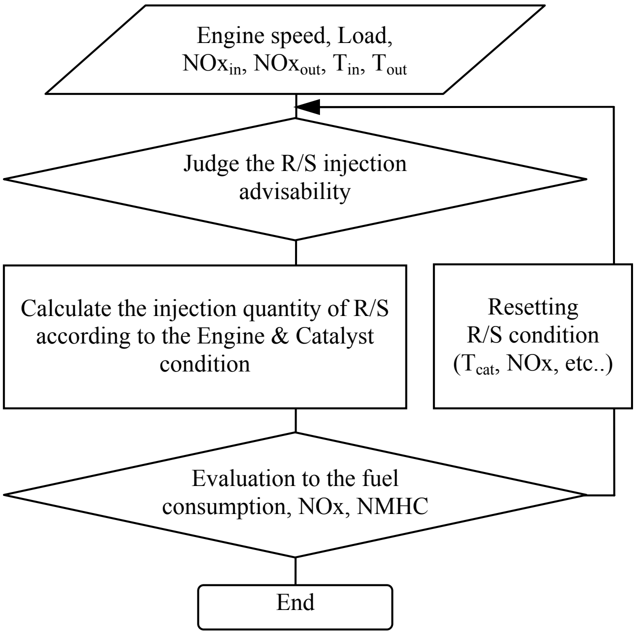


Fig.6 Flow chart of NSR system control

- Reynolds equation with turbulent momentum

$$\frac{\partial(\rho U_i)}{\partial t} + U_j \frac{\partial(\rho U_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j} - \rho\overline{u_i u_j}\right) \qquad (2)$$

- Boussinesq model

$$\rho\overline{u_i u_j} = \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij}, \quad \mu_t = \frac{C_\mu \rho k^2}{\varepsilon} \qquad (3)$$

- Transport equation of standard $k-\varepsilon$ model

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_i k)}{\partial x_i} = \rho P - \rho\varepsilon + \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] \qquad (4)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho U_i \varepsilon)}{\partial x_i} = C_{\varepsilon_1}\frac{\rho P \varepsilon}{k} - C_{\varepsilon_2}\frac{\rho\varepsilon^2}{k} + \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_i}\right) \qquad (5)$$

- Production term P in the equation (4) and (5)

$$P = \frac{\mu_t}{\rho}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3}\frac{\partial U_m}{\partial x_m}\delta_{ij}\right)\frac{\partial U_i}{\partial x_j} - \frac{2}{3}k\frac{\partial U_m}{\partial x_m} \qquad (6)$$

- Boundary conditions for standard $k-\varepsilon$ model;

$$k = 1.5(I \times U)^2, \ \varepsilon = \frac{C_\mu^{0.75} k^{1.5}}{L} \qquad (7)$$

Notation I is the turbulence intensity, Cμ stands for the turbulence coefficient, and L is the characteristic length.

Each coefficient is determined by general values of in-pipe flow as such.

$$C_\mu = 0.09, C_{\varepsilon_1} = 1.44, C_{\varepsilon_2} = 1.92, \sigma_k = 1.0, \sigma_\varepsilon = 1.3 \qquad (8)$$

- Turbulent mass diffusion model

$$\frac{\partial(\rho Y_i)}{\partial t} + \frac{\partial(\rho U_j Y_i)}{\partial x_j} = -\frac{\partial J_{ij}}{\partial x_i} + S_i, J_{ij} = -\left(\rho D_i + \frac{\mu_t}{Sc_t}\right)\frac{\partial Y_i}{\partial x_j} \qquad (9)$$

Notation D_i means diffusion coefficient of species i, and Sc_t is turbulent Schmidt number. Furthermore, in spray mode, WAVE model was used to simulate mixture formation.

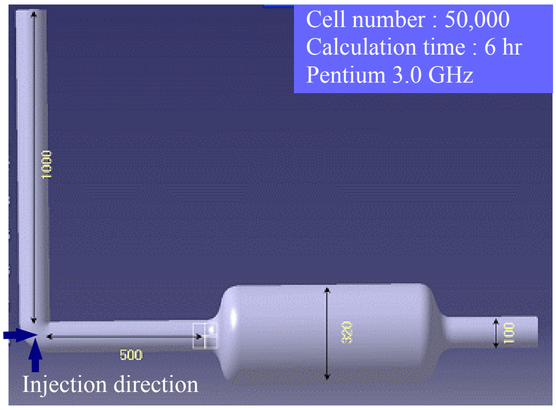


Fig. 7 Mesh generation of the catalyst and exhaust pipe

Table 4 Boundary condition of numerical analysis

Item	Specification
Inlet conditions	650K, 89.53 Pa gage
Exhaust gas	Air
Mass flow	14.0 m/s (Equivalent to 1400rpm)
Agent (injection vol.)	Octane($1.2 * 10^{-6}$ m^3)
Turbulence model	Standard k-ε model

Fig. 7 indicates 3-dimensional simulation model of the catalyst and exhaust pipe. Automatic grid generation technique is very useful to improve quality of grid without excessive increase in number of cells. In this study, GAMBIT, an automatic grid generator for FLUENT, generates the mesh into the CAD model of the catalyst. The re-mesh and layer methods enable increase or decrease of the number of cells according to the change of time. Other regions that have no change of geometry with respect to time have tetrahedral grids. Average number of cells is about 300,000. It costs about 35 hours to solve turbulent flow and diffusion during exhaust and intake processes divided into 1500 steps of time in a Pentium 3.0 GHz PC. The boundary and initial conditions of the analysis are summarized in Table 4.

4. RESULTS AND DISCUSSION

4.1. Basic characteristics of DME Engine

Figure 8 shows data for the following characteristics of the DME engine in the transient driving test: engine speed, load, NOx concentration from the engine, average temperature of the catalyst, and air/fuel ratio. These data were all obtained prior to the creation of rich spikes in the NSR catalyst system. From these results, it can be seen that the NOx has a behavior similar to the engine load (i.e. the temperature of the catalyst fluctuates in accordance with the engine load). The catalyst temperature, for instance, goes up to a maximum of 350deg. C at around 1500 seconds. At other times, however, the catalyst shows temperatures of 250deg. C or less. The air/fuel ratio comes close to the stochiometric air/fuel ratio of the DME(A/F: 8.9), due to an urgent acceleration and the high EGR rate.

4.2. Developing the NSR system

When establishing the NSR system, first of all, the effects of injection pressure (of rich spikes) and injection position on the NOx reduction performance was investigated. Figure 9 shows the effect of the injection pressure of the rich spike on the NOx reduction performance and THC. Because these results were obtained during development, NOx reduction performance is not so good. From the results, the reduction rate is clearly seen to be higher when injecting the rich spike at a high pressure of 12MPa. This is caused by the fact that the higher the injection pressure, the more NOx reducing agent is supplied per unit time. Thus, the higher injection pressure leads to rich spikes surpassing the stochiometric air/fuel ratio, which effectively reduces the NOx. On the other hand, at a low injection pressure of 2MPa, we observed that the air/fuel ratio did not reach the stochiometric air/fuel ratio by the rich spike sufficiently, thus not achieving a suitable environment for reducing NOx. This means that it is necessary to inject sufficient amount of NOx reducing agent per unit time.

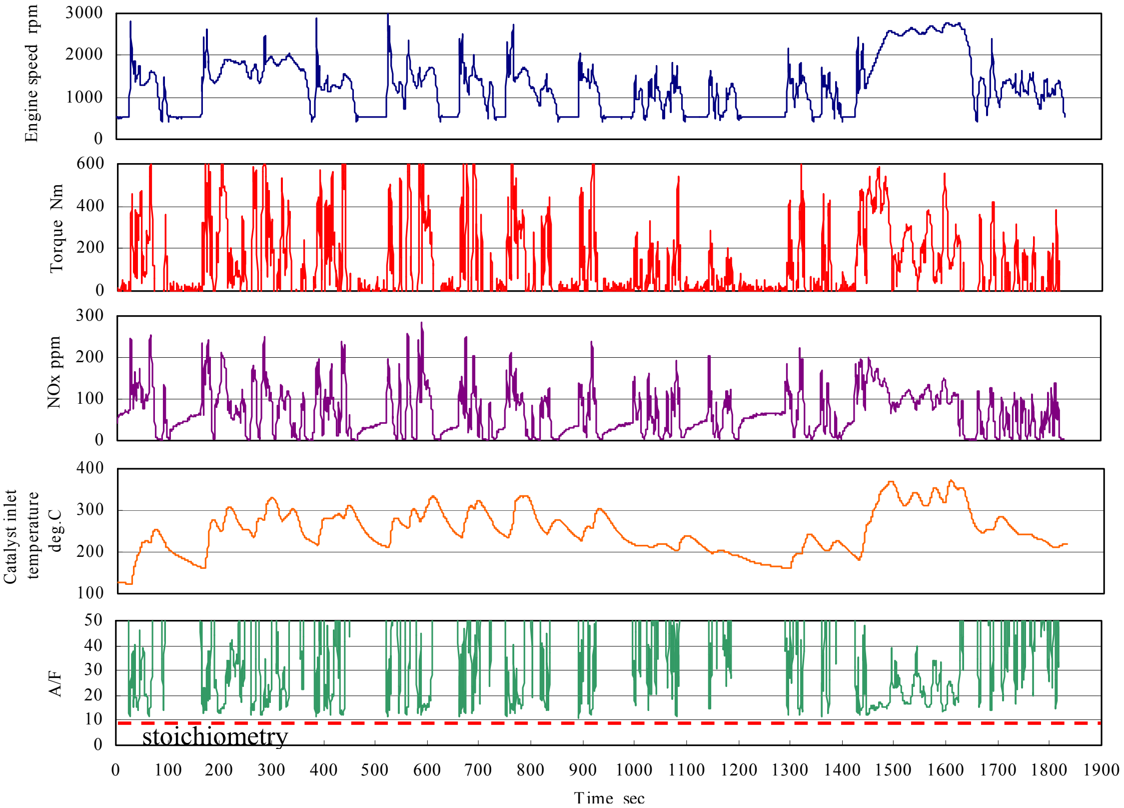
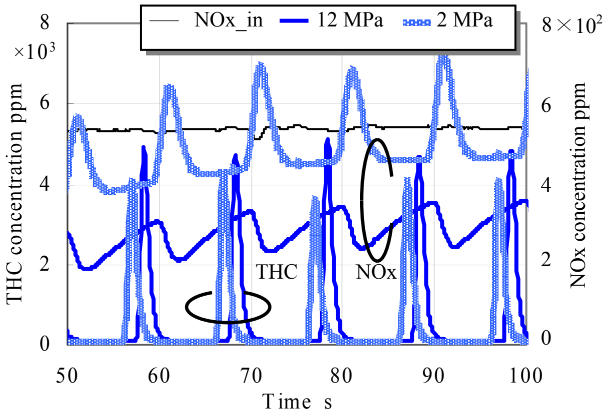
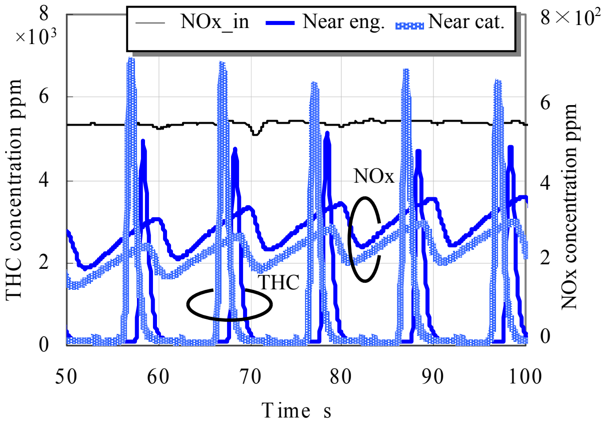


Fig. 8 Basic characteristics of DME engine on transient driving test (JE-05)

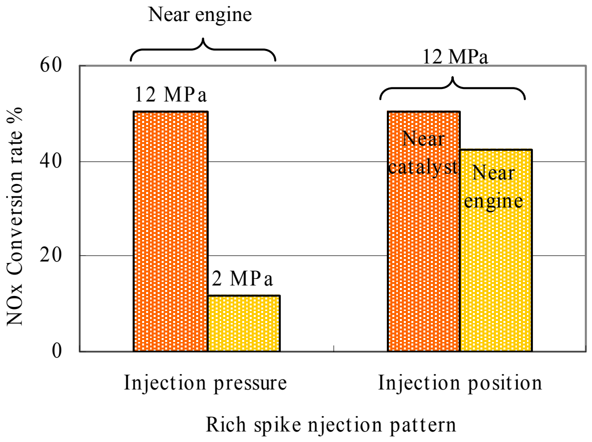


1080 rpm, 80% Load, R/S position: near Cat.
Fig. 9 Effect of rich spike injection pressure



1080 rpm, 80% Load, R/S pressure: 12 MPa
Fig. 10 Effect of rich spike injection position

Figure 10 shows the results of NOx reduction in accordance with the injection position of the rich spike (15cm before the NSR catalyst and 25cm after the turbocharger). NOx reduction performance is somewhat improved when the rich spike close to the NSR catalyst (immediately before the NSR catalyst). When the rich spike is injected immediately behind the exhaust manifold, which is away from the catalyst, oxidation of the injected fuel and mixing with the exhaust gas are promoted, which results in a lower concentration of THC at the entrance to the catalyst. This, in turn, results in a somewhat lower NOx reduction performance. The lower peak concentration of the THC also suggests this.



1080 RPM, 80% Load, $Inj_{duration}$ 15 ms
Fig. 11 Effect of rich spike injection pattern

The above results are summarized in Figure 11. Since the NOx reduction performance is higher when rich spikes are injected at higher pressure and at a location closer to the catalyst, the NSR system was installed on the basis of these results and optimization was attempted by control algorithms in transient driving tests.

4.2. Results of Simulation

Figure12 to 15 show the distributions of mixture when a rich spike injection applied for a catalyst in each pattern. A difference between figure 12 and figure 15 is being with and without stirring plate, figure 13 and figure 15 is curvature radius of exhaust pipe, figure 14 and figure 15 is direction of rich spike injection as shown in table 5.

Table 5 Effect of rich spike pattern and configuration of catalyst

	Pattern 1	2	3	4
Stirring plate	**w/o**	w/	w/	w/
Curvature radius	Large	**Small**	Large	Large
Injection direction	Opposite flow	Opposite flow	**Same to gas flow**	Opposite flow

Figure 12 shows a result when a rich spike is injected to opposite direction of an exhaust gas flow and without deflection plate. Mixture is concentrated on center of the catalyst and surrounding of catalyst is not used sufficiently. Figure 13 shows the effect of curvature radius on mixture condition. When a curvature radius of exhaust pipe is small, a mixture moved to bottom of pipe and catalyst because of the centrifugal force. Figure 14 shows the effect of injection direction of rich spike on mixture condition. Even though, surround of catalyst was used, but it is not sufficiently used. From these results, when rich spike injection is the opposite direction of exhaust gas, the curvature radius is long, and the stirring plate is applied, the mixture formation was favorable to be reacted by catalyst as shown in figure 15.

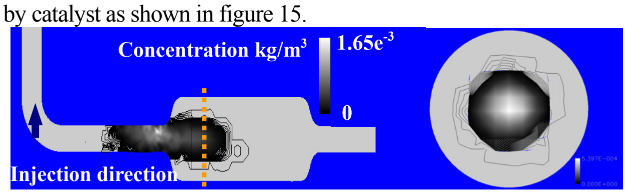


Fig. 12 Effect of rich spike injection pattern 1(Without stirring plate)

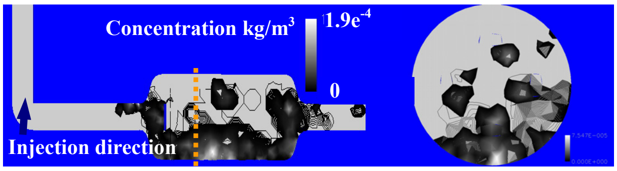


Fig. 13 Effect of rich spike injection pattern 2(Smaller curvature radius)

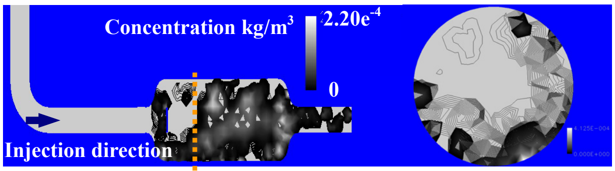


Fig. 14 Effect of rich spike injection pattern 3
(Direction of rich spike injection same to exhaust gas)

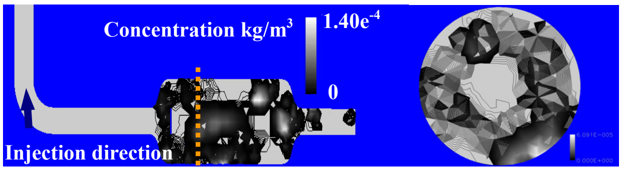


Fig. 15 Effect of rich spike injection pattern 4

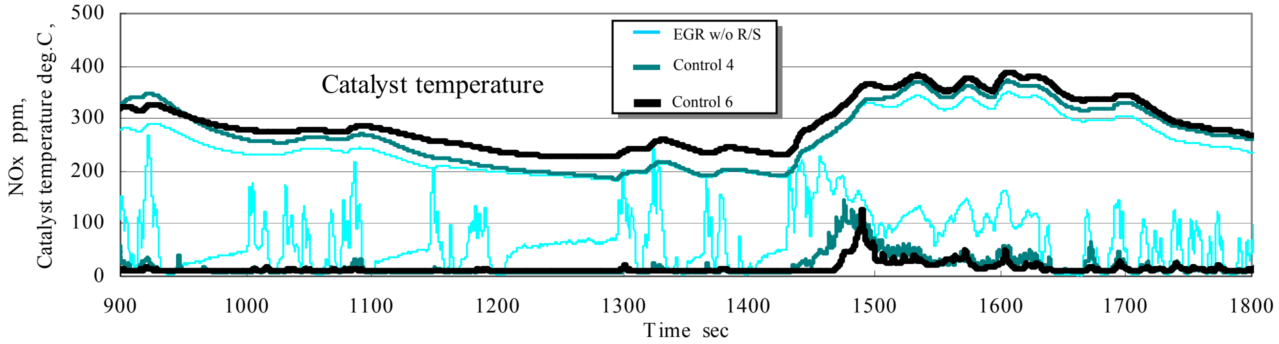


Fig. 16 Effect of rich spike injection pattern

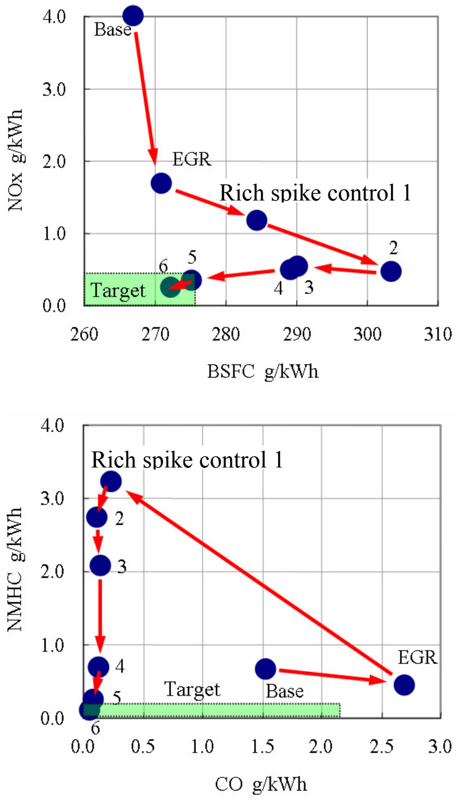


Fig.17 Exhaust gas & fuel consumption

4.3. Results of transient driving mode test

Figure 16 shows the time-series history of catalyst temperature and NOx concentration in the transient driving mode test. As the control algorithm is improved from versions labeled EGR to Control 6, the average catalyst temperature rises and the NOx reduction performance improves. In rich spike algorithm, the following control was used. In the driving where a rich regeneration condition cannot take place effectively, but, NOx storage process take place (i.e. during idling and low load condition), the catalyst was made to absorb or store NOx. However, in the range where the catalyst temperature is over around 300deg. C where a rich regeneration can be applied, the NOx reducing agent is injected in accordance with the engine driving conditions. This means the average temperature of the catalyst became higher and the NOx reduction performance improved accordingly. At the same time, by insulating the exhaust system and increasing volume of NSR catalyst, the catalyst was further activated and it was possible to reduce the NOx to 0.35g/kWh, well below the goal value of 0.5 g/kWh. R/S is applied effectively around 1450-1600 second where the engine was operated at high load and high speed. Figure 17 shows the results of DME engine emissions and fuel consumption when NSR system is applied in the transient driving mode, which is planned to be adopted as test mode of the New Long-Term Regulations in 2005 year (JE-05 Mode). From the graph which shows the relation between NOx and fuel consumption including rich spike quantity, although the fuel consumption deteriorates somewhat due to high EGR, the NOx has been reduced more than 50%. If rich spike control is applied thereafter, there is a tendency for the NOx to be reduced but a trade-off relation between NOx and fuel consumption was appeared (EGR → control 2). By refining and optimizing the rich spike control, however, the target values set in this research were achieved during the final stage(control 2 → 6). Also, by the optimization of algorithm, fuel penalty can be reduced to less than 1% of fuel consumption compare to only EGR condition. As far as CO is concerned, the target value of 2.22g/kWh was sufficiently cleared as the catalyst was activated by the rich spike control. Although the target value of 0.17 g/kWh for NMHC also was achieved. Thus, by using the NSR system and control algorithm, it was possible to achieve the target values for NOx, CO and NMHC.

5. CONCLUSIONS

The NSR system for DME engine was evaluated under transient driving mode test. The following conclusions were obtained.

(1) With post fuel injection in exhaust pipe, the high injection pressure and the rich spike closer to the NSR catalyst shows the better NSR performance.

(2) From the CFD simulation results, to improve the NSR catalyst performance, the direction of rich spike injection and installation of stirring plate was important factors to design the catalyst system.

(3) It is possible to reduce NOx, CO and NMHC emissions less than 0.5, 0.22 and 0.17g/kWh respectively by controlling the rich spike injection precisely.

(4) Fuel penalty can be reduced to less than 1% of fuel consumption.

ACKNOWLEDGMENTS

The authors would like to thank Bosch Japan Co. and Nissan Diesel Co. for their support for this research. Further thank to Mr. Kojima and Hiroki Kobayashi of the National Traffic Safety & Environment Laboratory during the experimental period.

REFERENCES

(1) Y. Sato *et al.*, Performance and Emission Characteristics of a DI Diesel Engine Operated on Dimethyl Ether Applying EGR with Supercharging, SAE 2000-01-1809.

(2) S.C. Sorenson *et al.*, Performance and Emissions of a Direct Injection Diesel Engine Fuelled with Neat Dimethyl Ether, SAE Paper 950064.

(3) “FLUENT user’s manual v. 6.2.,” FLUENT research Corporation, 2003.