A Study on the Optimal Injection Conditions for an HC-LNT Catalyst System with a 12-Hole Type Injector *

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Abstract
NOx catalytic converter systems periodically require rich or stoichiometric operating conditions to reduce NOx. The HC (hydrocarbon) concentration in a diesel engine is typically so low that the HC is not sufficient for NOx conversion. It was proposed that a rich air fuel ratio in a diesel engine could be realized via post fuel injection or supplemental fuel injection into the exhaust gas. A new method that optimizes the control of an external HC injection to diesel exhaust pipes for HC type LNT (Lean NOx Trap) catalyst systems has been developed. The external injection has other benefits: it can be controlled independently without disturbing engine control, it can be adapted to various layouts for exhaust systems, it has no oil dilution problems, among other benefits. In this study, the concentration and amount of HC can be controlled via control of the external injection. This research investigated the spray behavior of hydrocarbons injected into the transparent exhaust pipe. From this experiment, we obtained useful information about the optimal injection conditions for the HC-LNT catalyst system with an MPI injector.

Key words: Diesel Engine, LNT Catalyst, External Injection, After Treatment, Spray Behavior, RMS(Root Mean Square) Image

1. Introduction

As the environmental problems caused by automotive engine become more severe, exhaust emission standards and fuel economy regulations will become more stringent. Therefore, efforts to improve the thermal efficiency and reduce the emissions of internal combustion engines are being continued around the world with the goal of mitigating the effects of global warming and minimizing air pollution. The direct injection (DI) diesel engine has become a prime candidate for future transportation needs because of its high thermal efficiency. However nitrogen oxides (NOx) increase in the local high temperature regions and particulate matter (PM) increases in the diffusion flame region within diesel combustion1). Therefore, there has been increased demand to develop a suitable after treatment device 2).

To cope with the emission legislation for diesel passenger vehicles in the near future, the demand for a more efficient removal of NOx by catalytic systems has increased. NOx absorbing catalysts are based on the concept of NO storage and release making it possible to...
reduce NOx emissions in net oxidizing gas conditions. This technology is promising because it can give high NOx conversion efficiency. Another merit of this technology is using diesel fuel itself as a reducing agent. This De-NOx system, called the HC-LNT (Hydrocarbon-lean NOx Trap) catalyst, absorbs NOx in lean exhaust gas conditions and releases NOx in rich exhaust gas conditions. When NOx is released, if there is a sufficient supply of reducing agent, the released NOx will reduce to N₂. However, if the concentration of reducing agent is insufficient, the released NOx will pass through without conversion. Excessive amounts of reducing agent will slip through the LNT without the benefits of conversion and cause additional emission problems. Thus, the right amount of reducing agent should be supplied into the catalytic convertor3)~5).

The external injection approach to control the amount of HC agent has several prior benefits: it can be controlled independently without disturbing the engine control, can be adapted to various exhaust system layouts, and has no oil dilution problems6).

In this research, a characteristic of HC-LNT with a 12-hole type injector, which has good atomization characteristics at low pressure, was examined and methods of controlling the injection were studied. NOx reduction characteristics and atmospheric spray pattern were analyzed simultaneously, by using various light sources and a high-speed camera7~8). From this experiment, we obtained useful information about the optimal injection conditions for an HC-LNT catalyst system with a 12-hole type injector.

2. Experimental apparatus and procedure

2.1. Spray characteristics

The macro-scale parameters of the spray including the spray penetration length and cone angle were investigated by a high speed video camera using a xenon lamp with a large illumination range. As illustrated in Fig. 1, the illuminated droplets in the spray scatter the light into the optics creating a negative image of the spray. The developing process of the spray was observed by direct photography using a high speed video camera (Phantom 7.0) with a xenon lamp. In addition, a pulse delay generator (BNC, Model 555) synchronized a high speed video camera and injector driver. Images are acquired at a grabbing rate of 10,000 and 20,000 fps with an exposure time of 10 μs. The captured images are 256 by 512 pixels.

![Fig. 1 Experimental setup for the spray visualization system.](image)

This research used a 12-hole MPI (Multi Point Injection) prototype injector. The tip geometry and configuration of the nozzle are confidential. The experiments, with the exception of the injection test in the exhaust pipe, were performed with ISO 4113 proof oil, which is used as the working fluid instead of diesel fuel because its properties of density...
and viscosity are very similar to those of diesel fuel. A pipe with an inside diameter (I.D) of 4mm was employed as a fuel line. In addition, experiments were conducted at atmospheric pressure and room temperature.

<table>
<thead>
<tr>
<th>Table 1 Nozzle spec. and experimental conditions</th>
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<tbody>
<tr>
<td>Nozzle type</td>
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<tr>
<td>Spray geometry</td>
</tr>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Inj. pressure</td>
</tr>
<tr>
<td>Inj. frequency</td>
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<tr>
<td>Inj. duration</td>
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<tr>
<td>Pipe diameter</td>
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</table>

### 2.2 Droplet size measurement

The laser diffraction method was used to measure the Sauter mean diameter (SMD), which is the diameter of a uniform equivalent droplet with the same total volume and the same surface of all drops, as shown in equation (1).

\[
SMD = \frac{\sum nD^3}{\sum nD^2}
\]  

(1)

In this study, a Malvern instrument (Mastersize 2000) was used to measure the SMD and droplet size distribution. This technique uses a “far-field” diffraction pattern (the Fraunhofer diffraction pattern) that is formed when drops are illuminated by a parallel beam of coherent light to determine the droplet size distribution. Fig. 2 shows the optical system and the principle of the Malvern system used in this study.

The instrument measures the variation in angular scattering as a function of particle size for a group (ensemble) of particles and allows sampling at rates up to 2500 Hz. The laser light source was a He-Ne laser and has a 5-mm diameter. Therefore, the laser diffraction method was used mainly to identify the integrated droplet size distribution within the spray. SMD measured the average sizes of 1000 times per sample when the Obscuration ratio was more than 5% of the overall spray. The experimental setup for the Malvern system is shown in Fig. 3.
The system consists of a laser light source, a detector, a fuel supply system and an image processing unit. Several measurements at different locations are required to obtain the overall spray SMD distribution. Thus, a 2-axis traverse system was used to change the measurement position.

The measurement points were a total of 40 points located at 3-mm intervals in the radial direction, and at 10 mm intervals from 30 mm to 60 mm in the axial direction from the nozzle tip in the case of measuring the spray diameter as shown in Fig. 4.

The injection frequency and duration was 10 Hz and 10 ms, and the pressure increased to 0.5 bar from 4 bar. The obtained spray images were analyzed by software installed on the PC. Table 2 shows the detailed specification for the Malvern system used in this study.

### Table 2 Specification of Malvern system.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mastersizer 2000(Malvern)</th>
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</thead>
<tbody>
<tr>
<td>Size range</td>
<td>0.02 ~2000um, depending on material property</td>
</tr>
<tr>
<td>Measurement principle</td>
<td>Mie scattering</td>
</tr>
<tr>
<td>Detection system</td>
<td>Back scattering</td>
</tr>
<tr>
<td>Light source</td>
<td>Helium neon laser</td>
</tr>
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</table>
2.3 Digital image processing

2.3.1 RMS (Root Mean Square) image

In order to acquire the maximum spray dispersion angle and compare the spray shape, a root-mean-square (RMS) average image was used during the whole injection period. The RMS average is used to produce full-resolution averages of an ensemble of frames using equation (2). As a result, color of averaged image changes from blue to red with increase in the fuel concentration.

\[
S_{\text{RMS}}(x,y) = \sqrt{\frac{\sum S(x,y)^2}{n}}
\]

Where, \(S_{\text{RMS}}(x,y)\) is the RMS averaged spray image, \(S(x,y)\) is the spray (foreground) image after correcting and de-noising, and \(n\) is the number of images.

2.4 Experimental engine and after treatment system

The schematic of the experimental engine and after-treatment system is shown in Fig. 5. A 2L Diesel engine with a common rail system was used and MEXA-7200 was used as the exhaust gas analyzer. The after-treatment system was composed of catalytic converters and an external injection system. A CPF (Catalytic particle filter) was located upstream of the external injector, DFC (Diesel Fuel Cracking catalyst), and LNT.

As shown in Figure 6, a spray visualization system in the exhaust pipe consists of a visualization tube (pyrex) in order to investigate the injected spray pattern in the exhaust pipe and a high-speed video camera to acquire a spray image. Compressed air was supplied to the injector in order to cool it. The experimental conditions are described in Table 3.
Table 3 Experimental conditions.

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Inj. pressure</td>
<td>4 bar</td>
</tr>
<tr>
<td>Inj. frequency &amp; duration</td>
<td>40 Hz, 10 ms</td>
</tr>
<tr>
<td>Number of injection</td>
<td>80</td>
</tr>
<tr>
<td>Inj. interval (rich-lean interval)</td>
<td>60 sec</td>
</tr>
<tr>
<td>Temp. of reductant</td>
<td>40 °C</td>
</tr>
<tr>
<td>RPM of engine</td>
<td>2000 rpm</td>
</tr>
<tr>
<td>Attached angle of injector</td>
<td>0°, 10°, 20°, 30°, 45°</td>
</tr>
</tbody>
</table>

3. Results and discussions

3.1 Spray behavior characteristics

3.1.1 Spray developing process

Figure 7 indicates the effect of injection pressure on spray development for both the leading edge (ASOI (after start of injection), 3ms) and steady state (ASOI, 35ms). The injection pressure was changed at 4, 4.5, 5, 6, and 7 bar. The ambient pressure and the injection duration were fixed at 1 bar and 65 ms, respectively. The captured images have 256 x 512 pixels with 8 bits of grey scale resolution, and the measurement area has a size of approximately 27mm x 54mm. The spray images show that the spray shape and the atomization process were dominated by the liquid breakup from the jet. In addition, as the injection pressure increased, the spray tip penetration length increased and breakup length decreased and the droplet distribution widened. These phenomena occurred because the relative velocity between the air and the injected liquid jet increased with increases of the injection pressure. This prototype injector has the 2-spray pattern of a typical MPI injector and liquid columns clearly appeared.

Fig. 7 Spray developing process according to supply pressure.
3.1.2 Spray angle
The spray angle was measured to predict the position of wall wetting when the HC reductant was injected into the exhaust pipe. The spray angle was defined as the maximum dispersion angle in the RMS averaged spray image. The spray edge was detected by the Canny filter in the image processing system, and this boundary edge determines the spray angle. Figure 8(a) shows the RMS averaged image data during a pulse injection duration (65 ms) under different injection pressure conditions. In addition, Figure 8(b) shows the variations of the overall spray angle with respect to the fuel pressure. The quantified spray angles were acquired from Figure 8(a) using the Canny filter. The images in Figure 8 have 256 x 512 pixels. As the injection pressure increased, the overall spray angle increased according to the expanded spray dispersion area.

![RMS image](image1)

(a) RMS image

![Edge image](image2)

(b) Edge image

Fig. 8 Spray angle with various supply pressures.

3.1.3 Spray tip penetration
The measurement results of the spray tip penetration using the image processing technique are presented in Fig. 9. The injection duration was 65 ms (a pulse injection duration) and the interval for all other image was 0.1 ms. Since the increased injection pressure caused longer penetration lengths, the spray velocity increases.

![Penetration length](image3)

Fig. 9 Spray tip penetration lengths at various fuel supply pressures.
3.2 Spray mean diameter

The SMD profile of injection was also examined. The SMD represents the average droplet size (an exact measure of the evaporation rate). A small SMD means a small droplet size and larger surface area with respect to the volume of the droplets.

Figure 10 and Figure 11 show the SMD distribution for various injection pressures and different distances from the nozzle at 10 ms after the start of injection. As shown in this SMD distribution, the injection flow rates of this nozzle are concentrated on the center of a 2-spray column. In addition, the center lines of the 2-spray column are relatively symmetric.

As a result of these figures, the SMD was found to decrease as the injection pressure increases. In addition, at measuring points far downstream from the nozzle, the SMD decreased. This behavior can be explained by the fact that droplet break up occurs in the first 60 mm from the nozzle tip.

The differences within the drop size between locations at the centre and periphery of the spray were very large and the drop sizes increased with increasing radial distance from the spray centerline. Air entrained by the spray pulls the smaller drops toward the centerline, while the larger drops maintain their momentum and are directed along the periphery of the spray.

Fig. 10 Comparison of the SMD with various injection pressure.
3.3 Engine experiment

Several test points were selected from the steady states of the NEDC mode. A diesel engine (2.0ℓ, Common rail direct injection system) was used for this test. The NOx absorbing catalyst was aged in a furnace at over 700℃ for 20 hours. The activation temperature of the LNT is between 200℃ and 400℃. This temperature window can be shifted by adjusting the composition of the precious metal loading.

A high level of atomization and vaporization of the injected droplets must be advanced before the droplets get into the DFC because a gasified fuel can be converted into a reducing agent more effectively than the liquid state. For this purpose, the injector was installed in the 90° elbow pipe just before the DFC. Furthermore, placing the injector in this location assists in the prevention of wall wetting.

3.3.1 Distribution characteristics in the exhaust pipe and NOx reduction characteristics

To confirm distribution characteristics of the reductant in the exhaust gas flow, a part of exhaust pipe (I.D : 60mm) is visualized as can be seen in Figure 6. Figure 12 and Figure 13 show RMS averaged images, which were acquired though experiments; Figure 12 is the case of the 90° bended exhaust pipe in which the injector was installed, and Figure 13 is the case of the straight exhaust pipe with a distance of 10 cm to 20 cm from the injector tip. All images in Figure 12 and 13 have 512 x 256 pixels with 8bits of grey scale resolution. The measurement area in Figure 12 and 13 has a size of approximately 150mm x 75mm.

As shown in the image of an attached angle of 0°, the direction of the injected fuel was curved downward. It could be stated that the centrifugal force affects the flow field in the curved part. Because of this effect, wall-wetting was seen in the bottom. Therefore, we changed the attached angle from 0° to 45° in order to find the optimal spray distribution.
about the attached angle of the injector.

In the case of an attached angle of 0°, the spray was widely distributed in the exhaust pipe. The spray distribution region shows a tendency to decrease as the attached angle increases. The distribution range was decreased by approximately 23%, when the attached angle was changed from 0° to 45°. This result indicated that the reductant concentration decreases because wall wetting increases owing to an impingement on the surface of the exhaust pipe according to the increase in the attached angle.

![Fig. 12 RMS images of each attached angle of a 90° bended exhaust pipe.](image)

![Fig. 13 RMS image of each attached angle between 10cm and 20cm from the injector.](image)
Figure 14 and Figure 15 show emission characteristics of the THC and NOx after the LNT Catalyst. When the reductant was injected, the concentration of the THC and NOx tended to form an instantaneous maximum peak value, which was regarded as a slipping phenomenon in the regeneration of the LNT Catalyst. After the peak concentration decreased to a minimum value, it then increased slowly and it finally decreased again. This fluctuation pattern was caused by the loss of reductant, which was vaporized after the wall wetting.

In the case of an attached angle of 0°, the losses of reduction due to wall wetting were the smallest because the re-falling pattern was almost invisible, and the NOx conversion efficiency was the best, as shown in Figure 17.

As a result, NOx conversion efficiency decreases when the attached angle of the injector was increased because the reductant concentration decreases which corresponds to increased wall wetting.

NOx concentration also decreases as the injection of reductant continues. However, the emission of the THC increases. This results in the slip of THC. The higher concentration of reductant leads to the more slip of THC. The injection of reductant has some control parameters: injection frequency and the number of injection. The number of injection determines the total quantity of THC, and the injection frequency determines the concentration of injected reductant. High NOx conversion efficiency, low slip of THC and low reductant consumption can be achieved by optimizing two parameters above.

Fig. 14 Effect of the attached angle on NOx reduction.

Fig. 15 Effect of the attached angle on THC emissions.
3.3.2 Effect of change in injection pressure on the spray behavior characteristics in the exhaust pipe

Figure 18 shows the effect of the injection pressure on the spray behavior characteristics in the exhaust gas flow. Engine speed was at 2000rpm and the flow rate and temperature of the exhaust gas are same conditions in this experiment. Pictures at the left side are show spray patterns by injection pressure during the same injection period, figures at the right side are RMS averaged images of visualization pictures. All images have 512 x 256 pixels with 8bits of grey scale resolution.

As discussed before, increase in the injection pressure leads to increase in both the spray angle and the spray tip penetration. It is responsible for increase in wall wetting as is seen in Figure 18.

Also, the injected fuel is curved downward. Centrifugal force might affect the flow field in the curved part, which might cause more the wall-wetting as is seen in the bottom.

Furthermore, the NOx conversion efficiency will increase because the SMD increases and the surface area of the reductant is getting wider as the injection pressure increase as shown in Figure 11, but it can predict that the loss of reductant increases because the wall wetting increases.
4. Conclusions

This paper investigated the optimal injection conditions with a 12-hole type injector for HC-LNT catalyst. We formed the following conclusions:

1) As the injection pressure increased, the spray angle increased because the spray dispersion area expanded and the breakup process of spray column became faster.
2) As the injection pressure increased, the spray penetration length became longer, and the spray velocity was faster.
3) The mean diameter of the droplets decreased as the injection pressure increased, as the distance from nozzle tip moves downstream.
4) In case of an attached angle 0°, the spray was widely distributed in the exhaust pipe and NOx conversion efficiency was best.
5) As the attached angle of injector increased, the spray distribution region decreased and NOx conversion efficiency was reduced.

Acknowledgement

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References

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