

Combustion Technologies for Euro IV-compliant Direct Injection Diesel Engine

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ABSTRACT

In fall 2003, Honda introduced a passenger vehicle diesel engine to the European market. During the development of this engine, research was conducted on combustion technologies to reduce fuel consumption, combustion noise and emissions.

By adopting pilot injection while also advancing the start of main combustion event, fuel consumption and combustion noise are both lowered, but emissions performance was not improved. Dispersion of the air-fuel mixture and the extension of the appropriate period for dispersion ensured a lean local air-fuel ratio which resolved the emissions issue.

The use of these combustion technologies has enabled fuel consumption and engine out emissions to be reduced with no increase in combustion noise. Fitted in a 1 590 kg equivalent inertia class vehicle in combination with the catalyst, the vehicle satisfied the 2005 European diesel exhaust emissions standards (EURO IV), and achieved a low fuel consumption of 5.4L / 100 km and superb quietness.

1. Introduction

The high speed direct injection (HSDI) diesel engine has become widely accepted throughout the European market as it offers low fuel consumption and substantial low speed torque. Furthermore, combustion noise has been reduced with a series of recent technical developments. The amount of market share HSDI's claim is increasing year by year, and is expected to approach 50% by the year 2010. Exhaust emission systems have improved in accordance with the passing of more stringent regulations; however, as further improvements in emissions are required, developments in both after-treatment systems^{(1)–(4)} as well as improvements in combustion^{(5)–(11)} are being pursued. Unfortunately, many

developments in these areas lead to a reduction in fuel economy.

In the development of this engine, low fuel consumption, the hallmark of a diesel engine's value, was dramatically improved. Additionally, the improvement in combustion has enabled a reduction in both combustion noise and engine emissions.

2. Experimental Equipment

2.1. Test Engine

The main specifications of the Accord i-CTDi diesel engine⁽¹²⁾ used for testing are shown in Table 1.

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Table 1 Main specifications of Accord i-CTDi diesel engine

Cylinder configuration	Inline 4
Displacement volume	2200cm ³
Bore × Stroke	85.0mm × 97.1mm
Compression ratio	16.7
Fuel injection equipment	Common rail (Max. pressure 160MPa)
Nozzle type	Micro mini-sack
Turbocharger	With variable nozzle
Swirl control valve	Continuously variable
EGR valve	Electric control
EGR cooler	Without bypass valve

2.2. In-Cylinder Visualization Apparatus and 3D CFD Code

As can be seen in Fig. 1, in-cylinder fuel spray and luminous flame were observed from directly above the cylinder head using an endoscope as a visualization apparatus. Also, using an Image Intensifier (I.I.) the visualization was amplified 3 000 times to observe non-luminous flame and high temperature areas. In addition, 3D CFD was utilized to estimate the behavior of the fuel spray as well as the air-fuel mixture.

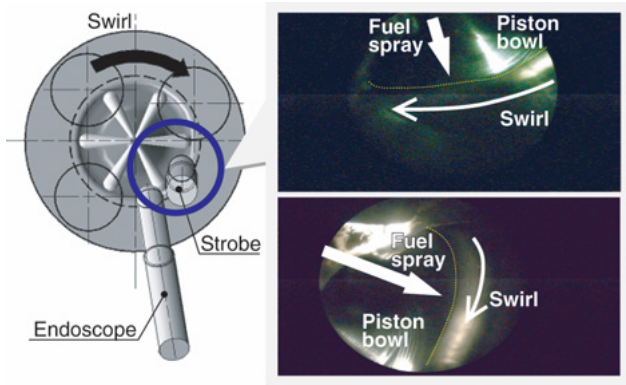


Fig. 1 Experimental setup for observation manuscript

3. Combustion Improvement Concepts

3.1. Pilot Injection Improves Fuel Economy and Reduces Combustion Noise

Figure 2 shows the relationship between brake specific fuel consumption (BSFC) and the maximum rate of in-cylinder pressure increase ($dP/d\theta_{max}$) when amount of fuel, EGR ratio (%), and main injection timing are varied. The relationship between BSFC and NOx is given in Fig. 3. BSFC is greatly affected by the start of combustion event, and reaches a minimum at a prescribed start of combustion event. This prescribed start of combustion event is defined as θ_{min_bsfc} in this paper.

When pilot injection is not used, $dP/d\theta_{max}$ is high at θ_{min_bsfc} and combustion noise deteriorates. Therefore, injection timing in current diesel engines is retarded from θ_{min_bsfc} .

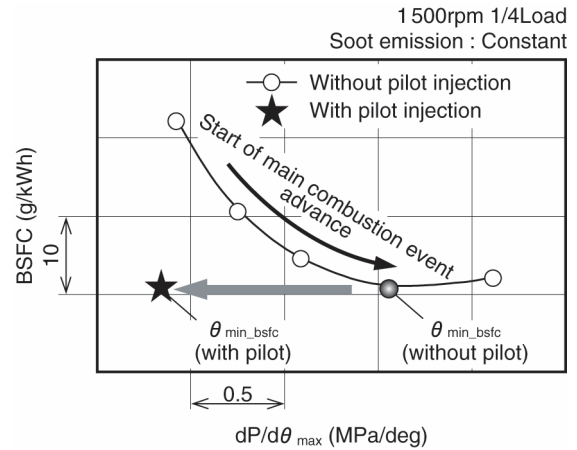
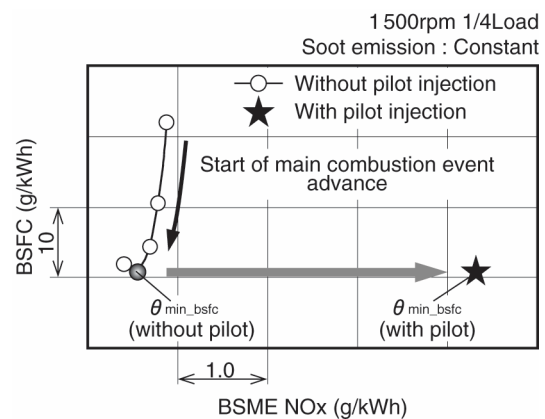
Fig. 2 Effect of pilot injection on $dP / d\theta_{max}$ and BSFC

Fig. 3 Effect of pilot injection on NOx and BSFC

The ★ shows the BSFC, $dP/d\theta_{max}$, and NOx for the case where pilot injection was utilized and the main injection timing was adjusted to allow the start of combustion timing to be θ_{min_bsfc} . The $dP/d\theta_{max}$ improves at an equivalent BSFC compared to the case where pilot injection is not used; however, while the insoluble organic fraction (soot) is constant, the amount of NOx greatly increases.

As explained above, it was found that the employment of pilot injection and the setting of start of combustion event to θ_{min_bsfc} enables simultaneous achievement of lowered combustion noise and fuel consumption. The issue concerning how to reduce emissions is discussed below.

3.2. Reduced Emissions from Promoted Dispersion of Air-fuel Mixture

The effect of the nozzle cone angle in relation to the piston bowl on emissions was investigated.

Figure 4 shows the shape of the piston bowl and the specifications of the nozzle used in testing. The shape of the piston bowl effectively utilizes the penetration ability of the spray that strikes the wall of the bowl, and promotes the mixing of air with the fuel spray. Concerning the nozzle specifications, a micro-sack nozzle was used because its variability in the fuel spray for each hole is small and it minimizes the amount of fuel dribbling from the sack volume. Sufficient nozzle hole area to enable full power output was ensured.

Figure 5 shows the NOx emissions for cases where the nozzle cone angle was set to be 7 degrees wider and for the

case where it was set to be 10 degrees narrower than the nozzle cone angle α , for the same level of soot generation. As a result, NOx is minimized by using the cone angle α .

In order to analyze this phenomenon, in-cylinder visualization as well as a simulation were performed. The simulation results of the air-fuel mixture behavior for each cone angle, are shown in Fig. 6. Also, the results of visualization for the cone angle α and that of $\alpha - 10$ degrees are shown in Fig. 7.

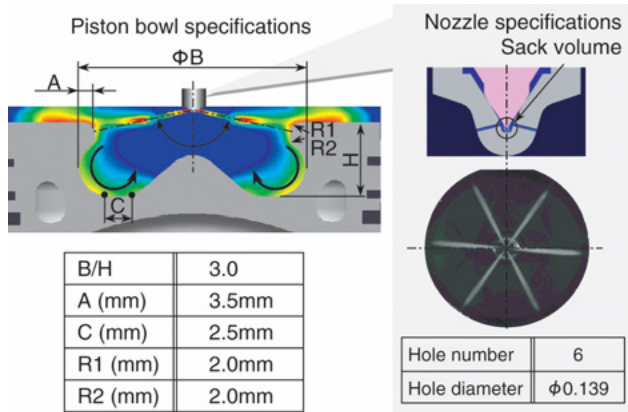


Fig. 4 Specifications of piston bowl and nozzle

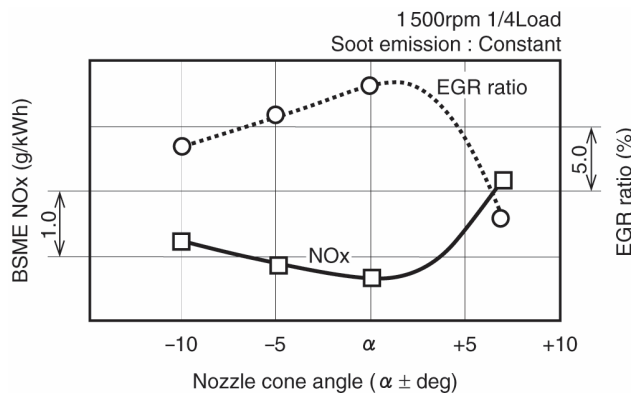


Fig. 5 Effect of nozzle cone angle on NOx

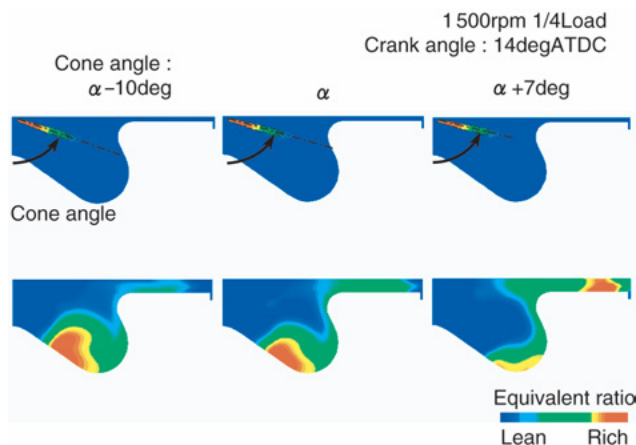


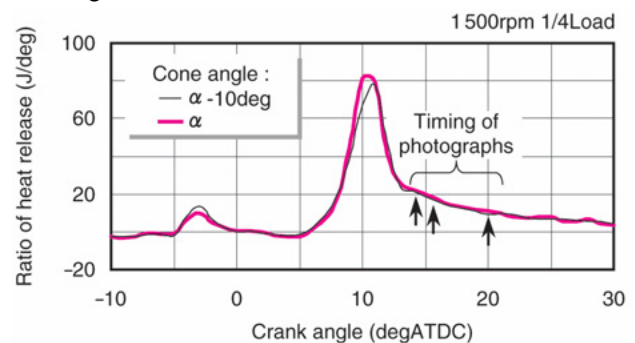
Fig. 6 Effect of nozzle cone angle on mixture distribution

From the simulation results in Fig. 6, it was found that most of the injected fuel spray stays inside the piston bowl for the $\alpha - 10$ degrees case. For the cone angle α , when the spray strikes the wall of the piston bowl it flows out of the bowl and lastly for the $\alpha + 7$ degrees case, the ratio of released air-fuel mixture greatly increases. In other words, an excessively narrow nozzle cone angle leads to the formation of an over rich mixture inside the bowl. Also, an excessively wide nozzle cone angle leads to the formation of an over rich mixture outside the piston bowl. After all, the cone angle α leads to the best distribution of air-fuel mixture inside and outside of the bowl. Therefore, it is considered that this enables increasing the amount of EGR, which leads to a reduction in NOx.

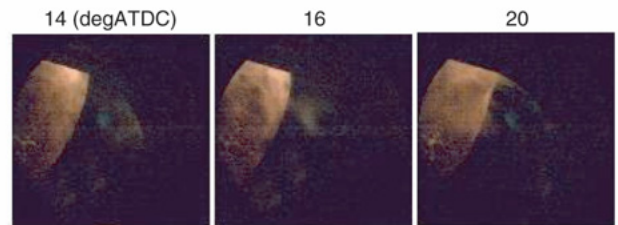
The in-cylinder visualization results in Fig. 7 show the generation of a dark luminous flame that includes a quantity of soot inside the bowl for the case of $\alpha - 10$ degrees. These results can be explained by the combustion of a rich mixture inside the bowl.

In comparison, for the case of the cone angle α , the luminous flame is released outside the bowl, leaving the flame brightness higher inside the bowl. Also, as the heat release ratio is more active, it is considered that the air/fuel ratio of the mixture inside the bowl becomes leaner through the flow of air-fuel mixture leaving the bowl and the mixture inside the bowl becomes more favorable.

It is normally considered that forcing combustion to take place inside the bowl reduces emissions and is therefore better; however, from the results of this test, it was found that to achieve a balanced mixture both inside and outside the bowl through the discharge of fuel spray is more effective for reducing emissions.



Cone angle : $\alpha - 10$ deg



Cone angle : α

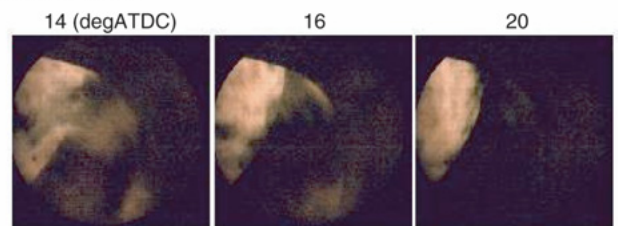


Fig. 7 Effect of nozzle cone angle on flame behavior (CCD camera)

3.3. Reduced Emissions from Increased Dispersion Period of Air-fuel Mixture

In order to reduce NOx with a constant level of soot through increasing the amount of EGR, it is necessary to reduce the amount of fuel spray injected after the start of main combustion event. Therefore, as can be seen in Fig. 8, an indicator of the amount of fuel injected after the start of main combustion has been defined as $\theta_{\text{eoi_soc}}$.

Figure 9 shows the relationship between $\theta_{\text{eoi_soc}}$ and NOx emissions, while varying the EGR ratio, the pilot injected amount, and the injection timing for the pilot as well as the main injections, under the condition of constant soot level. From these results, a shorter $\theta_{\text{eoi_soc}}$ enables increasing the EGR ratio and therefore NOx is reduced.

Figure 10 shows the relationship between the pilot heat release ratio (ratio of heat generated by pilot combustion and total heat generation) and $dP/d\theta_{\text{max}}$ for the same experiment.

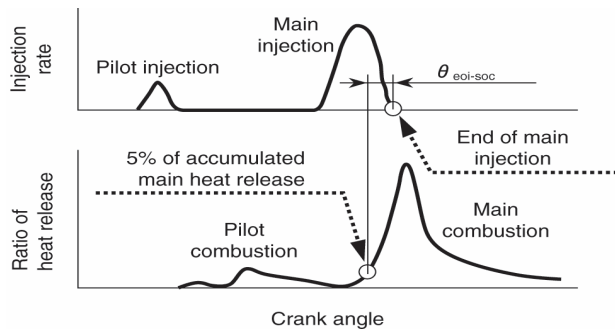


Fig. 8 Definition of $\theta_{\text{eoi_soc}}$

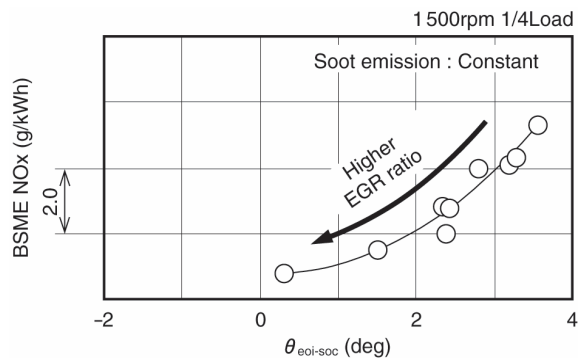


Fig. 9 Effect of $\theta_{\text{eoi_soc}}$ on NOx

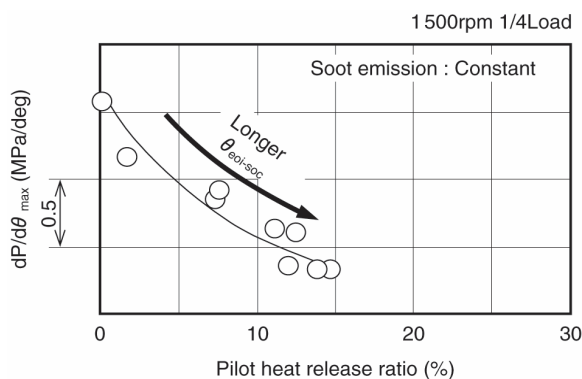


Fig. 10 Effect of pilot heat release ratio on $dP/d\theta_{\text{max}}$

When the pilot heat release ratio is increased, $dP/d\theta_{\text{max}}$ does decrease, however, $\theta_{\text{eoi_soc}}$ is lengthened. In other words the pilot heat release ratio and $\theta_{\text{eoi_soc}}$ are inversely proportional.

It was considered that in order to shorten $\theta_{\text{eoi_soc}}$ in conjunction with an increase in the pilot heat release ratio, a reduction in the in-cylinder temperature would be effective. Therefore, with the combinations of compression ratio and EGR cooling shown in Table 2, testing was performed with changes made to the pilot injection amount and injection timing. In order to maintain fuel economy, the main injection timing was adjusted so that a constant start of main combustion event was maintained. In addition, the EGR ratio was adjusted to maintain a constant soot level.

Figure 11 shows the test results. Smaller compression ratios and higher efficiency of the EGR cooler lead to shorter $\theta_{\text{eoi_soc}}$ for the same pilot heat release ratio. As a result, as can be seen in Fig. 12, NOx was reduced for a constant $dP/d\theta_{\text{max}}$.

In order to analyze the phenomenon described above, combustion visualization tests and simulations were performed for a case where the compression ratio was 18.0 with an EGR cooler efficiency of 39% and a case with a compression ratio of 16.7 with an EGR cooler efficiency of 50%. EGR and injection timing were adjusted so that the soot and $dP/d\theta_{\text{max}}$ would be equal for each of the cases.

Table 2 Compression ratio and EGR cooler efficiency

NO.	Compression ratio	EGR cooler efficiency (%)
1	18.0	39
2	16.7	50
3	15.5	50
4	14.5	50

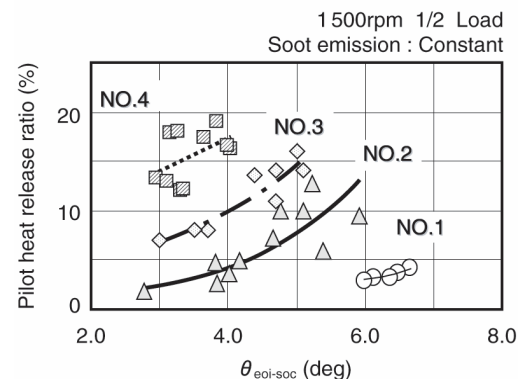
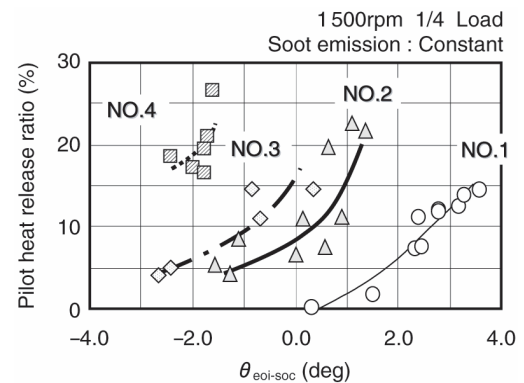


Fig. 11 Effect of compression ratio and EGR cooler efficiency

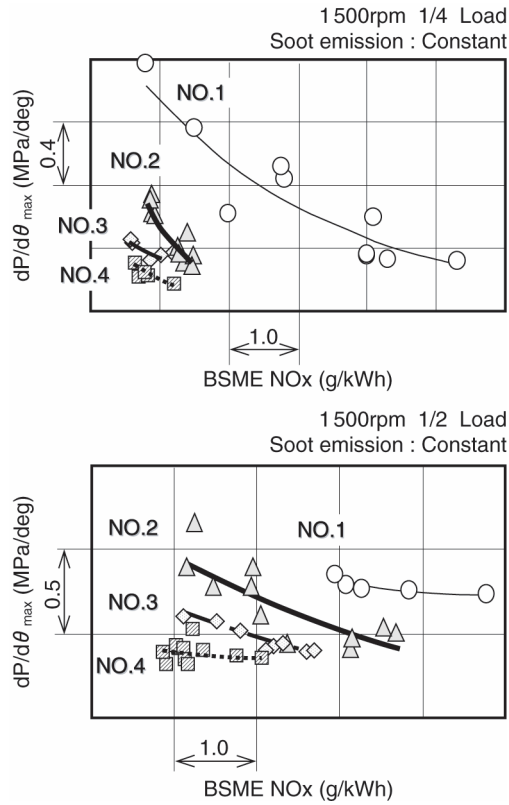


Fig. 12 Effect of compression ratio and EGR cooler efficiency on NOx and $dP/d\theta_{max}$

The observation results using a CCD camera for both cases are shown in Figs. 13(a) and 14(a). The observation results of equipping the CCD camera with an I.I. are shown in Figs. 13(b) and 14(b). Also, the simulation results of the spray behavior are shown in Figs. 13(c) and 14(c).

For the case where the compression ratio is 18.0 with an EGR cooler efficiency of 39%, the pilot spray is ignited near the walls of the combustion chamber and combustion is occurring accompanied with a slight amount of luminous flame. From the photograph of the pilot combustion taken using I.I., active non-luminous combustion directed from the walls to the center of the combustion chamber can be seen. The main fuel spray directed towards the piston bowl wall is ignited before coming into contact with the walls of the piston bowl and was surrounded by luminous flames. This is considered due to the speeding up of the ignition of the main fuel spray as it was injected into the high temperature environment of the cylinder generated from the pilot combustion.

In comparison, for the case of a compression ratio of 16.7 with an EGR cooler efficiency of 50%, a weak non-luminous combustion is seen near the combustion chamber walls after the pilot spray struck the wall and a luminous flame during the main combustion is seen only after the main spray is completely finished. This phenomenon is considered to be due to low temperature combustion of the pilot spray near the walls, there was an increase in the delay in ignition of the main fuel spray.

It is considered that this suppresses the generation of soot, enabling an increase in the EGR ratio, therefore reducing NOx. In addition, it is estimated that because the

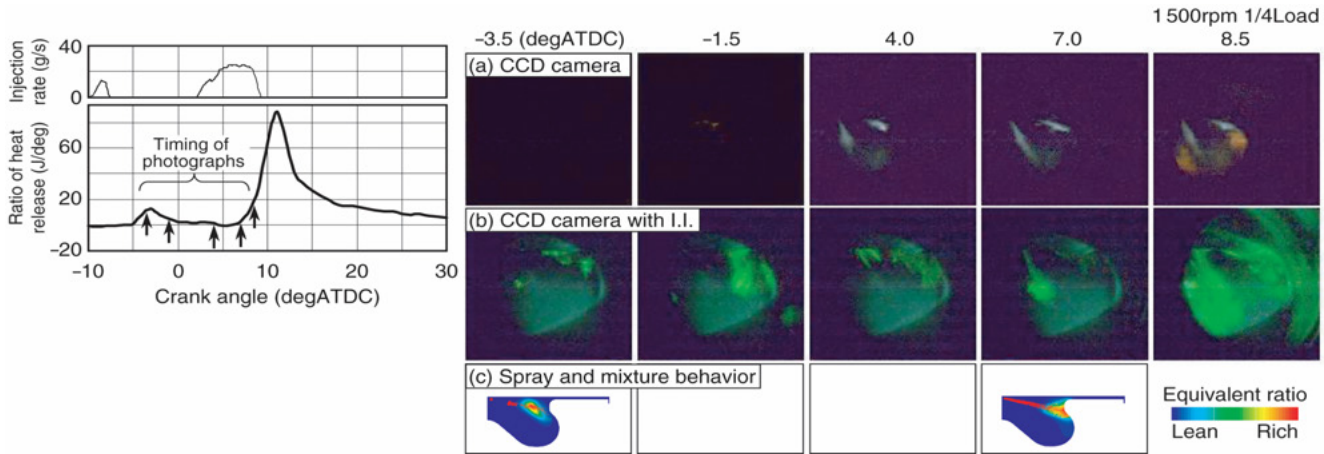


Fig. 13 $\epsilon 18.0$ flame behavior (CCD camera only and CCD camera with I.I.)

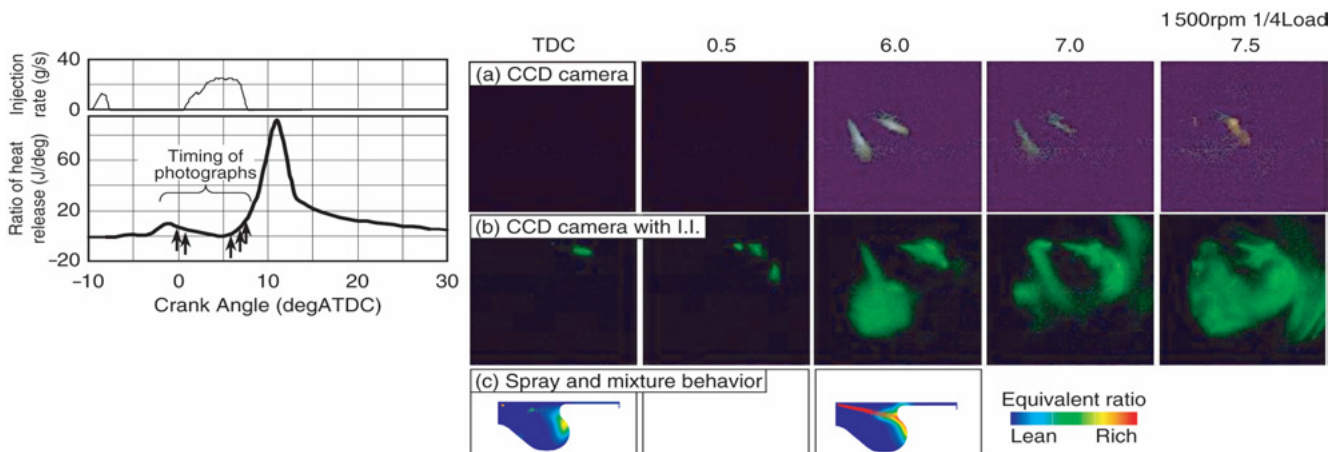


Fig. 14 $\epsilon 16.7$ flame behavior (CCD camera only and CCD camera with I.I.)

leading edge of the main fuel spray was ignited and the flame spread upstream, very rapid combustion was suppressed, enabling $dP/d\theta_{max}$ to be maintained.

It was found that it was possible to reduce NOx without causing $dP/d\theta_{max}$ to deteriorate through increasing the efficiency of the EGR cooler and reducing the compression ratio. However, because excessive reduction in the compression ratio increases the generation of white smoke, HC and CO while the engine is cold, as well as reducing fuel economy, the compression ratio for this engine was set at 16.7.

4. Performance of the New Engine

The main specifications of the engine were set according to the results as discussed in the previous section and are shown in Table 1. Figure 15 shows the full load performance of this engine. Also, Figs. 16 and 17 show fuel economy, combustion noise, and emissions performance at partial load. A Modern European diesel engine was used as a reference for comparison. The results show that this engine has a similar level of combustion noise while fuel consumption and emissions have been reduced.

This engine is being used in the European Accord starting last fall. Fuel economy, emission, and power output performance are shown in Figs. 18 and 19. In addition to the reduction in emissions described so far, the after-treatment

system mounted under floor and directly beneath the engine has enabled this engine to meet 2005 European diesel exhaust emissions standards. And at the same time, while it belongs to 1 590 kg equivalent inertia weight class, it has achieved the fuel economy of a C category vehicle, 5.4L/100 km.

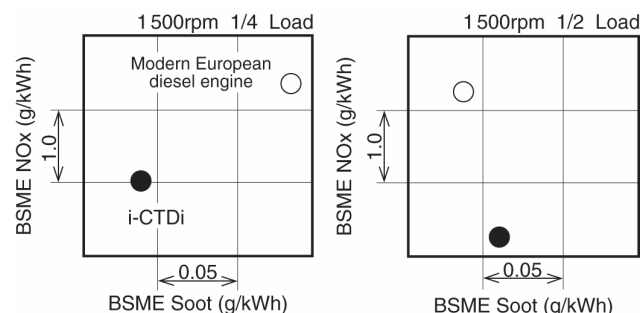


Fig. 17 NOx and soot under partial load

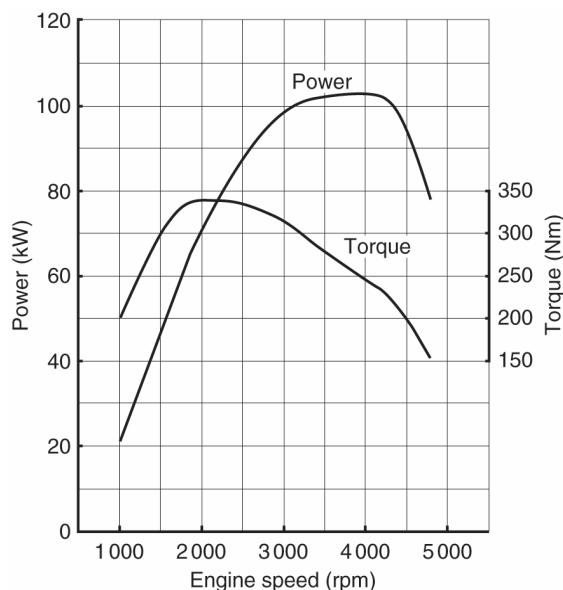


Fig. 15 Full load performance

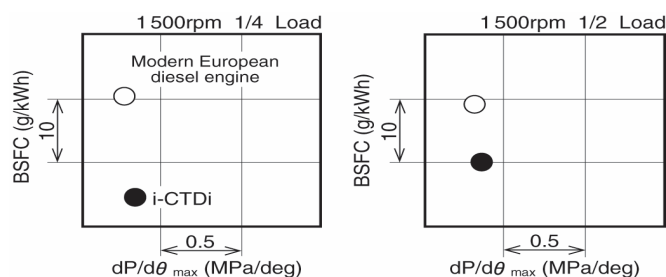


Fig. 16 BSFC and $dP/d\theta_{max}$ under partial load

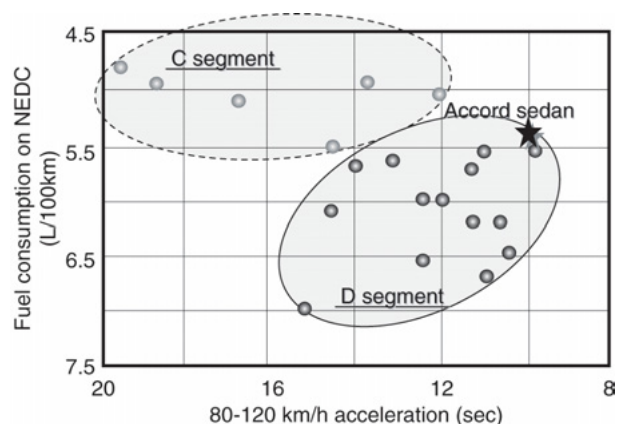


Fig. 18 Fuel consumption and performance of Accord sedan

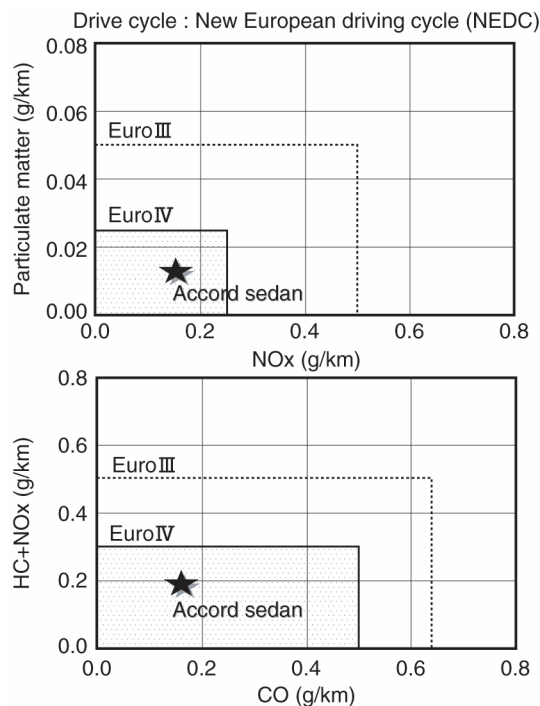


Fig. 19 Accord sedan emissions

5. Conclusion

With the prerequisites of low fuel consumption and low combustion noise, technology that meets the 2005 European emissions standards was developed. The items learned through this development are summarized below.

- (1) Utilization of pilot injection and advancement of start of main combustion event enables both low fuel consumption and low combustion noise. The deterioration in generation of soot in conjunction with this can be reduced through the acceleration of the dispersion of the air-fuel mixture.
- (2) Acceleration of the dispersion of the air-fuel mixture
 - (a) Through dispersing an appropriate amount of fuel spray out of the piston bowl, a lean local air-fuel ratio is ensured, therefore generation of soot is reduced. As a result, it is possible to increase EGR enabling a reduction in NOx for an equivalent level of soot.
 - (b) The reduction of $\theta_{\text{coi-soc}}$ enables an increase EGR ratio, resulting in a reduction of NOx for an equivalent level of soot.
 - (c) Increasing the pilot heat release ratio results in lowering $\text{dP/d}\theta_{\text{max}}$. However, because $\theta_{\text{coi-soc}}$ gets longer, the amount of NOx for an equivalent level of soot increases.
 - (d) In order to both shorten $\theta_{\text{coi-soc}}$ and increase the pilot heat release ratio, reduction of the compression ratio and cooling of EGR is effective.
- (3) This combustion technology is being utilized in the i-CTDi diesel engine that is used for the European Accord. While it belongs to a 1 590 kg equivalent inertia weight class vehicle, it meets the 2005 European emissions standards, and has achieved low combustion noise and a fuel economy of 5.4L/100 km.

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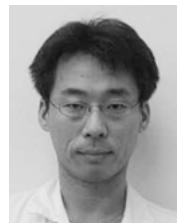
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