

Research on Expansion of Premixed Charge Compression Ignition (PCCI) Diesel Combustion Operation Range

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ABSTRACT

In the area of diesel engines, the reduction of soot and NOx emissions is demanded through the achievement of increased combustion performance. High expectations are placed on premixed charge compression ignition (PCCI) combustion as a combustion method that will achieve breakthrough reductions in NOx and soot emissions. However, the use of this combustion method is restricted to the low-speed, low-load range because it becomes challenging to realize an ignition delay and combustion noise increases as the engine load increases.

The research discussed in this paper attempted to expand the range of application of PCCI combustion by increasing exhaust gas recirculation (EGR) cooling performance and employing a low compression ratio. The results of the research indicated that it was possible to extend the application of PCCI combustion to virtually the entire operating range employed in the European NEDC and North American FTP75 modes.

1. Introduction

Concern towards environmental issues is growing on a global scale, and demand for diesel engines, which have a considerable effect in reducing CO₂ emissions and display outstanding dynamic performance, has increased in the past several years, in particular in Europe.

However, the reduction of polluting emissions, in particular soot and NOx, represents an issue for diesel engines. It is thought that lean NOx catalysts^{(1), (2)} and SCR systems⁽³⁾ will be effective measures in response to the introduction of more stringent emissions regulations in the future. However, when after-treatment systems are added, manufacturing costs increase, vehicle weight increases, and a variety of economic burdens cannot be avoided, for example for the construction of infrastructure for the supply of urea. This makes it necessary to develop technologies that will reduce NOx and soot emissions by increasing the efficiency of combustion to the greatest possible extent.

Against this background, a great deal of research has been conducted by automakers and research laboratories on PCCI combustion as a combustion method capable of reducing NOx and soot emissions^{(4), (5)}. However, given that the application of the method is restricted to the low-load range, and it presents issues from the perspective of

combustion stability during transient operation, a variety of issues remain to be resolved for its practical application.

The research discussed in this paper focused on one of the issues impeding practical application of the method, its restriction to the low-speed, low-load operating range, and attempted to reduce NOx and soot emissions across a wide range by extending the range of its application.

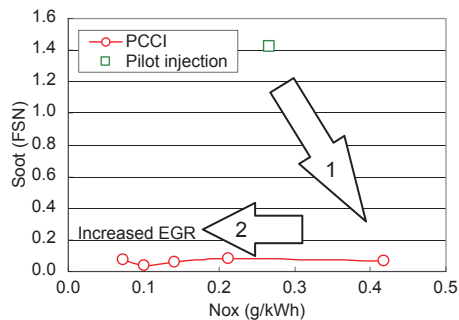
2. Range of Application of Conventional PCCI Combustion

This chapter will explain the mechanism of PCCI combustion based on combustion behavior at 1500 rpm and 25% load. Figure 1 shows a comparison of conventional diffusive combustion using pilot injection and PCCI combustion. Figure 1(a) shows the behavior of NOx and soot emissions, Fig. 1(b) shows the behavior of combustion noise ($dP/d\theta$ max), and Fig. 1(c) shows the distribution of the local equivalence ratio and the local temperature. PCCI combustion generates an ignition delay through comparatively early injection of the fuel, promoting mixture of the air and fuel and reducing soot formation in comparison to conventional combustion. However, because the air-fuel mixture with an equivalence ratio of close to 1 is higher at ignition, combustion is rapid, and NOx and

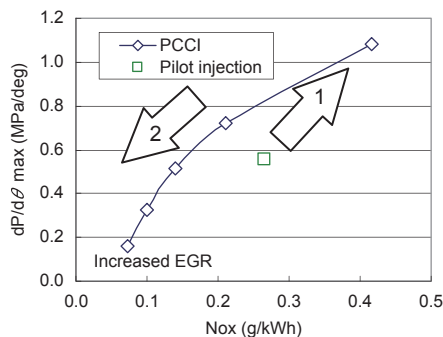
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$dP/d\theta$ max increase as a result (Arrow 1 in the figures). High-volume EGR is therefore introduced in order to control the rapid combustion and reduce NOx emissions and $dP/d\theta$ max⁽⁶⁾ (Arrow 2). By this means, it is possible to simultaneously reduce NOx and soot emissions in the low-speed, low-load range without increasing $dP/d\theta$ max.

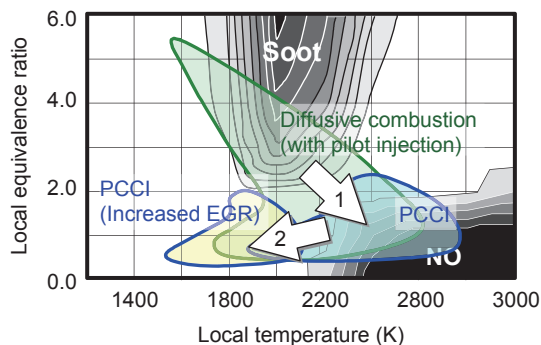
However, it becomes challenging to achieve an ignition delay as the engine load and speed increase. In addition, the air-fuel mixture with an equivalence ratio close to 1 increases with a greater volume of fuel, thus increasing the speed of combustion and raising $dP/d\theta$ max. This makes it challenging to expand the operating range in which PCCI combustion can be applied. Figure 2 shows the operating ranges of North American FTP75 mode and European



(a) NOx and soot emissions



(b) NOx and $dP/d\theta$ max



(c) Local temp. and local equivalence ratio

Fig. 1 Comparison between diffusive combustion and PCCI on soot, $dP/d\theta$ max and Φ -T map

NEDC mode. The curve in the upper section of the graph is the curve generated by full load at each engine speed. For the reasons discussed above, the application of PCCI combustion is limited to part of the low-speed, low-load range. Expansion of its range of application would therefore be desirable.

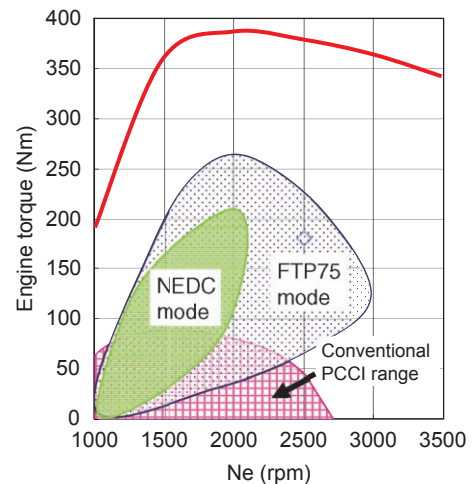


Fig. 2 Conventional PCCI combustion application range

3. Approach to Expansion of Range of PCCI Combustion

As discussed above, it is necessary to achieve an ignition delay and control the speed of combustion in order to expand the range in which PCCI combustion can be applied. Reducing the compression end temperature is an effective method of realizing an ignition delay. The project therefore attempted to increase the ignition delay by increasing the cooling performance of the EGR cooler and reducing the compression ratio, and to control the speed of combustion by increasing EGR^{(6), (7)}.

4. Test Engine, Test Fuel, and Test Conditions

Table 1 shows the specifications of the diesel engine used in tests. A 2.2-L prototype diesel engine was used as the basic framework. 1500 rpm/140 Nm and 2500 rpm/180 Nm were selected as representative test conditions that would cover virtually the entire range of FTP75 and NEDC modes.

5. Expansion of Range of Application of PCCI to High-speed, High-load Range

5.1. Effect of EGR Cooling

Figure 3 shows the results of comparison of $dP/d\theta$ max for PCCI and diffusive combustion at differing intake gas temperatures at 2500 rpm/180 Nm. In the case of diffusive combustion, the speed of main combustion can be

Table 1 Test engine specifications

Cylinder configuration	In line 4
Bore × stroke (mm)	85 × 96.8
Displacement (cm ³)	2197
Compression ratio	17.2, 16.2
Valve train	DOHC 4 valves
Fuel injection system	180 MPa common rail
Nozzle type	7 holes 680 cm ³ /sec
Intake system	Turbocharged, inter-cooled system
EGR cooling capacity	3.0 kW or 6.3 kW at 2500 rpm 180 Nm
Fuel properties	Cetane number: 44 Sulfur: 11.5 ppm

controlled by means of pilot injection, but combustion is rapid in the case of PCCI combustion. In the results shown in Fig. 3, as the cylinder intake gas temperature declines, the speed of combustion is reduced and $dP/d\theta$ max declines. Figure 4 shows the relationship between the cylinder intake gas temperature, combustion speed (with the period from a mass burn fraction of 5% to 90% as the index), and the EGR rate. Increasing the cooling performance of the EGR cooler produced a greater EGR mass flow in the cylinders, and the

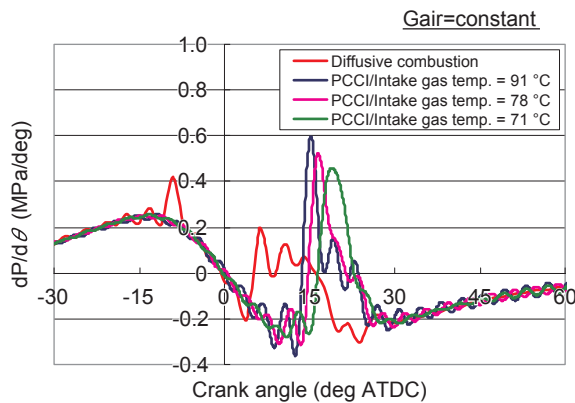
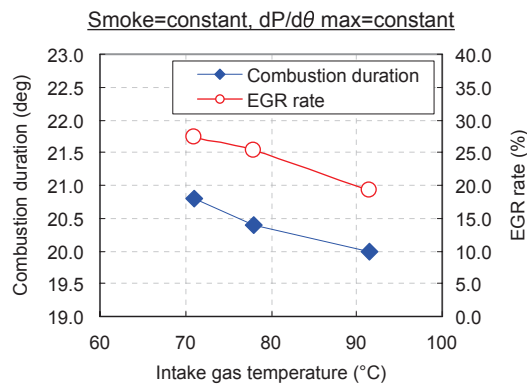
Fig. 3 Effect of intake gas temperature on $dP/d\theta$ 

Fig. 4 Effect of intake gas temperature on combustion duration and EGR rate

increase in the ignition delay (considered as the period from the completion of injection to a mass burn fraction of 5%) resulting from a reduction in the intake gas temperature reduced soot emissions. Because of this, it was possible to further increase EGR until the same level of soot emissions was reached, thus reducing the speed of combustion.

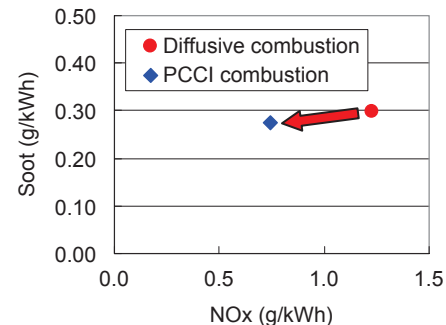
Figure 5 shows soot and NOx emissions and the relationship between break specific fuel consumption (BSFC) and $dP/d\theta$ max when EGR is cooled. Due to the effect of PCCI combustion, NOx emissions are reduced by 39% at the same level of soot emissions. However, fuel efficiency is reduced because the ignition timing must be retarded to control the increase in $dP/d\theta$ max.

The results discussed above indicate that increasing EGR cooling performance can be considered an effective method of expanding the range of application of PCCI combustion.

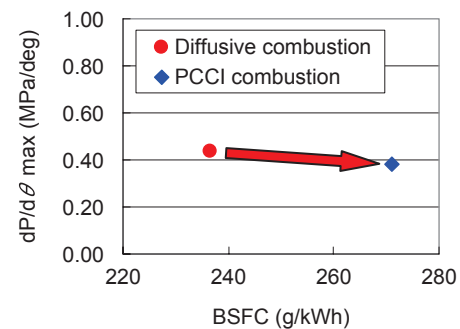
5.2. Low Compression Ratio

The compression end temperature can be reduced through the use of a low compression ratio, and this could be expected to increase the ignition delay. Figure 6 shows $dP/d\theta$ when the compression ratio is varied at 2500 rpm/180 Nm. The lower compression ratio produces an ignition delay, realizing slower combustion with a low $dP/d\theta$ max.

Figure 7 shows the relationship between compression ratio, ignition delay, and EGR rate at 2500 rpm/180 Nm.



(a) NOx and soot emissions

(b) BSFC and $dP/d\theta$ maxFig. 5 Effect of combustion pattern on emissions, BSFC and $dP/d\theta$ max

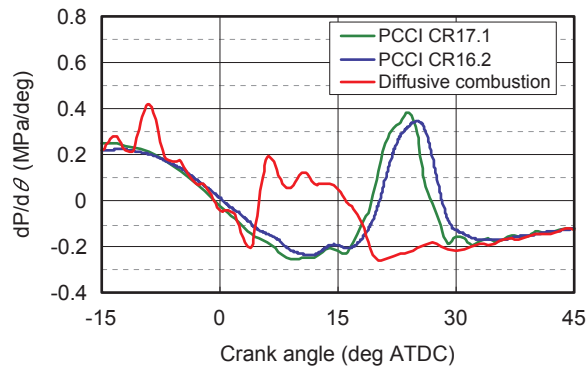
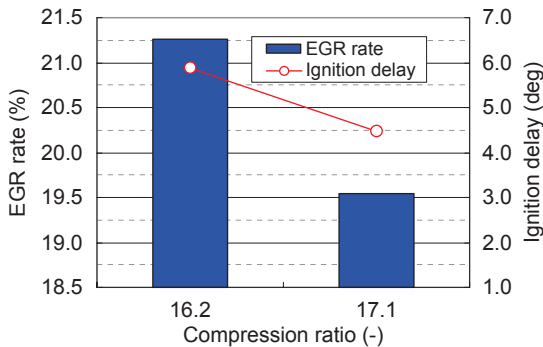
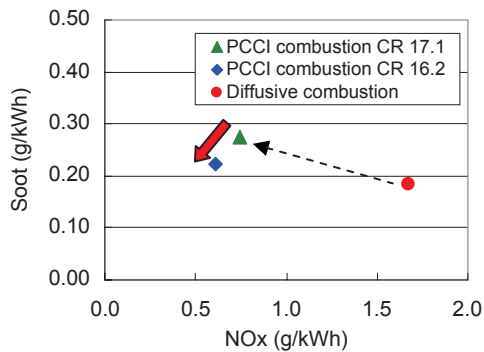
Fig. 6 Effect of compression ratio on $dP/d\theta$ 

Fig. 7 Effect of compression ratio on ignition delay and EGR rate



(a) NOx and soot emissions

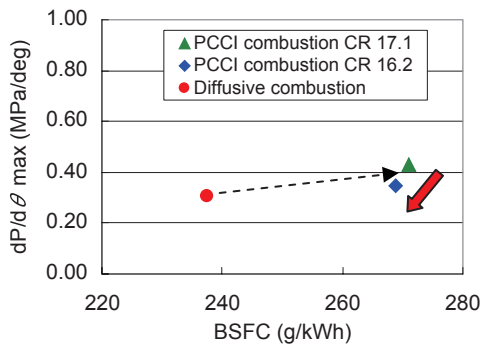
(b) BSFC and $dP/d\theta$ maxFig. 8 Effect of combustion pattern and compression ratio on emissions, BSFC and $dP/d\theta$ max

Figure 8 shows the relationship between emissions, fuel efficiency, and $dP/d\theta$ max at the reduced compression ratio. Reducing the compression ratio increases the ignition delay, promoting mixture of the air and fuel and reducing soot emissions. Because EGR can be increased until the same level of soot emissions is reached, it is possible by this means to reduce NOx and $dP/d\theta$ max.

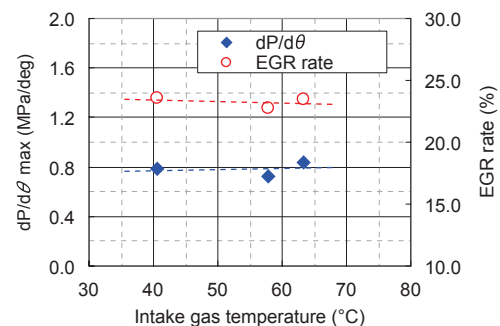
These results indicate that lowering the compression ratio can also be considered an effective method of expanding the range of application of PCCI combustion.

6. Expansion of the Range of Application of PCCI Combustion to the Low-speed, High-load Range

6.1. Issues of Application of PCCI Combustion in the Low-speed, High-load Range

The results obtained indicated that using the methods discussed above, it would be possible to expand the range of application of PCCI combustion to the high-speed, high-load range (as represented by 2500 rpm/180 Nm) without an increase in $dP/d\theta$ max, and that the soot-NOx tradeoff could be ameliorated. However, control of $dP/d\theta$ max in the low-speed, high-load range remained challenging. Figure 9 shows the relationship between cylinder intake gas temperature and EGR rate at 1500 rpm/140 Nm. Even when the cooling performance of the EGR cooler is increased, there is almost no change in $dP/d\theta$ max and only a slight increase in the EGR rate.

One reason that can be considered for this is a time factor. Because the piston speed is comparatively slow in the low-speed range, $dP/d\theta$ max necessarily increases in proportion with increasing loads at which a greater amount of fuel is injected for each unit crank angle, and the speed of combustion tends not to decline. In addition, the turbocharger employed in this project was not capable of supercharging sufficiently in the low-speed, high-load range. The air-fuel mixture therefore tended to become rich, and soot emissions increased with increased EGR. It would therefore be challenging to realize slower combustion by increasing EGR in this operating range, and it was considered that it would be necessary to employ pilot injection.

Fig. 9 Effect of intake gas temperature on $dP/d\theta$ max and EGR rate

6.2. Modification of Combustion Behavior using Pilot Injection

If the range of application of PCCI combustion is to be expanded to the low-speed, high-load range by increasing EGR cooling performance and lowering the compression ratio, it would be challenging to reduce $dP/d\theta$ max using single-stage injection. The use of pilot injection would be the most effective means of resolving this issue, but it would be unable to realize a sufficient ignition delay like PCCI combustion, and the combustion generated by pilot injection in the high-load range would produce increased soot emissions in proportion to the increase in the EGR rate. This project therefore attempted to ameliorate the NO_x-soot tradeoff by employing closed pilot injection, which is able to reduce soot emissions to a level below that of conventional pilot injection.

6.2.1. Mechanism of soot reduction through use of closed pilot injection

Figure 10 shows the rate of heat release and the rate of injection when the pilot interval is varied at 1500 rpm/140 Nm, and Fig. 11 shows NO_x and soot emissions. In diffusive combustion, the pilot spray is combusted prior to main combustion, and the increase in in-cylinder ambient temperature and ambient pressure promotes the ignition of main combustion. By contrast, in the case of closed pilot injection, the ignition of the pilot spray almost overlaps with main combustion. However, because the ignition

timing of main combustion remains virtually the same irrespective of the pilot interval, the ignition delay of main combustion cannot be increased using closed pilot injection. Nevertheless, as Fig. 11 shows, the use of closed pilot injection does reduce soot emissions against conventional pilot injection. This suggests the existence of a soot reduction mechanism other than the increase in the ignition delay, as indicated in Chapter 2.

An analysis was conducted using 3D-CFD (KIVA-3V code) in order to determine the reason for this phenomenon. The results are shown in Figs. 12 and 13. Figure 12 shows the distribution of the local equivalence ratio in the cylinders for each crank angle. The ratio of fuel is higher the higher the figures, and the ratio of the mixture with air increases as the figures become lower, indicating that homogenization is proceeding. At a pilot interval of 1500 μ s, main combustion occurs after the completion of pilot combustion. A similar pattern of combustion is observed at a pilot interval of 1000 μ s, but the distribution of the local equivalence ratio is higher than in the case of 1500 μ s, providing further confirmation of the increase in soot emissions shown in Fig. 11. At a pilot interval of 350 μ s, main combustion is ignited prior to the completion of pilot combustion, and the local equivalence ratio is lowest.

In order to analyze the reason for the difference in the local equivalence ratio at different pilot intervals, the concentration of CO₂, which provides an index of the burned gas in the cylinders, and its distribution were

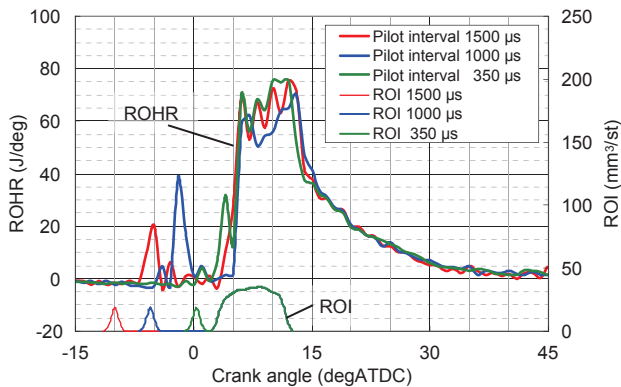


Fig. 10 Effect of pilot interval on rate of heat release and rate of injection

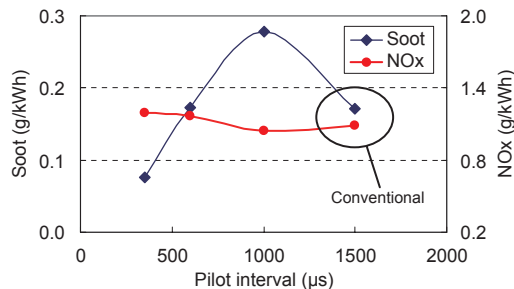


Fig. 11 Effect of pilot interval on NO_x and soot emissions

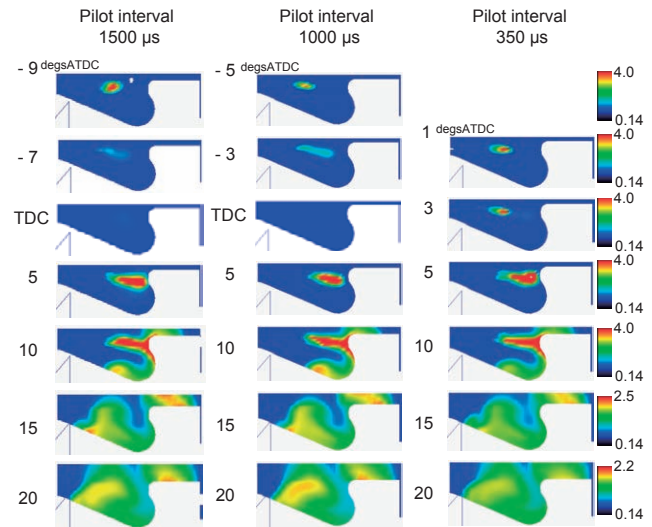


Fig. 12 Effect of pilot interval on local equivalence ratio in piston bowl

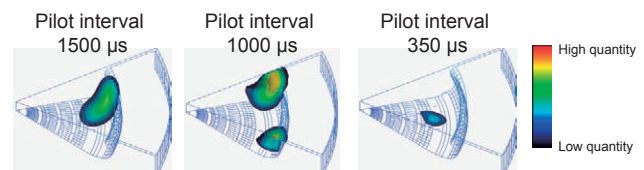


Fig. 13 Effect of pilot interval on CO₂ in piston bowl at 4 degATDC

calculated for 4 deg ATDC. The results are shown in Fig. 13. Compared to 1500 μ s, at a pilot interval of 1000 μ s the CO₂ concentration is higher and the distribution covers a wider range. It is thought that because the CO₂ concentration at 4 deg ATDC represents part of the composition of the gas in the cylinders close to the commencement of main combustion, if there is a large quantity of burned gas, the probability of contact between fuel and oxygen declines, and soot emissions increase. It can therefore be considered that if the pilot interval is reduced to 350 μ s, soot emissions will be controlled despite the fact that pilot combustion and main combustion are continuous because little burned gas exists at the time of commencement of main combustion.

As described above, the use of closed pilot injection reduces the amount of burned pilot gas introduced to the

main injection, thus controlling the local richness of the air-fuel mixture and reducing soot emissions.

6.2.2. Effects of application of closed pilot injection

The following effects were obtained from the application of closed pilot injection in the low-speed, high-load range. Figure 14 compares heat release at 1500 rpm/140 Nm for each combustion pattern. Figure 15 shows fuel efficiency and $dP/d\theta$ max. In the case of PCCI combustion using single-stage injection, rapid heat release cannot be controlled even when the ignition timing is retarded, and satisfactory $dP/d\theta$ max cannot be obtained. By contrast, the heat release rate of main combustion when closed pilot injection was used was approximately half that for PCCI combustion, and $dP/d\theta$ max and combustion speed were controlled to low levels.

Figure 16 shows soot and NO_x emissions. The combination of the effect of EGR cooling and the achievement of low-soot combustion through the use of closed pilot injection, while not matching PCCI combustion, did ameliorate the soot-NO_x tradeoff in comparison to diffusive combustion.

7. Effect of Expansion of Range of Application of PCCI Combustion

In order to expand the range of application of PCCI combustion, it was necessary to achieve an ignition delay and to control the speed of combustion by increasing EGR. The achievement of increased EGR cooling performance and the use of a low compression ratio were tested as means of realizing these goals. It was possible to increase the range of application of PCCI combustion to the high-speed, high-load range without any increase in $dP/d\theta$ max during steady-state operation. However, because it was challenging to control $dP/d\theta$ max in the low-speed, high-load range, closed pilot injection was employed in this range in addition to the methods described above in order to ameliorate the tradeoff between soot and NO_x without any increase in $dP/d\theta$ max. While not attempted in this project, it is considered that the possibility remains of extending the range of application of PCCI combustion to the low-speed, high-load range by increasing supercharging performance at low speeds.

Whatever methods may be used, the research discussed in this paper did indicate that it is possible to extend the range of application of PCCI combustion to almost entirely cover the operating ranges used in European NEDC Mode and North American FTP75 Mode (Fig. 17).

Figure 18 shows the reduction in soot and NO_x emissions and the effect on fuel efficiency of extending the range of application of PCCI combustion. It is clear that the effect of reduction of soot and NO_x emissions that was previously restricted to the low-speed, low-load range has been extended to the high-speed, high-load range.

Because closed pilot injection is employed in the

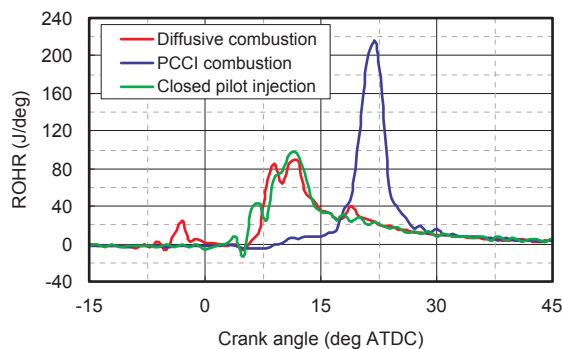


Fig. 14 Rate of heat release by each combustion pattern

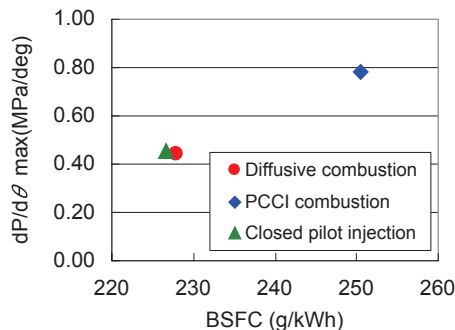


Fig. 15 Effect of combustion pattern on BSFC and $dP/d\theta$ max

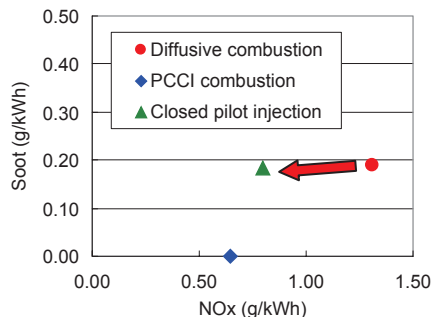


Fig. 16 Effect of combustion pattern on emissions

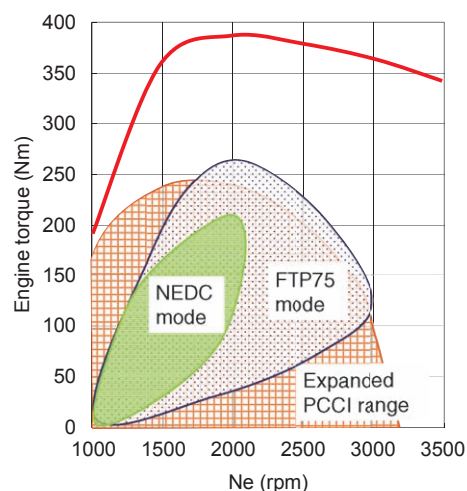


Fig. 17 PCCI combustion application range

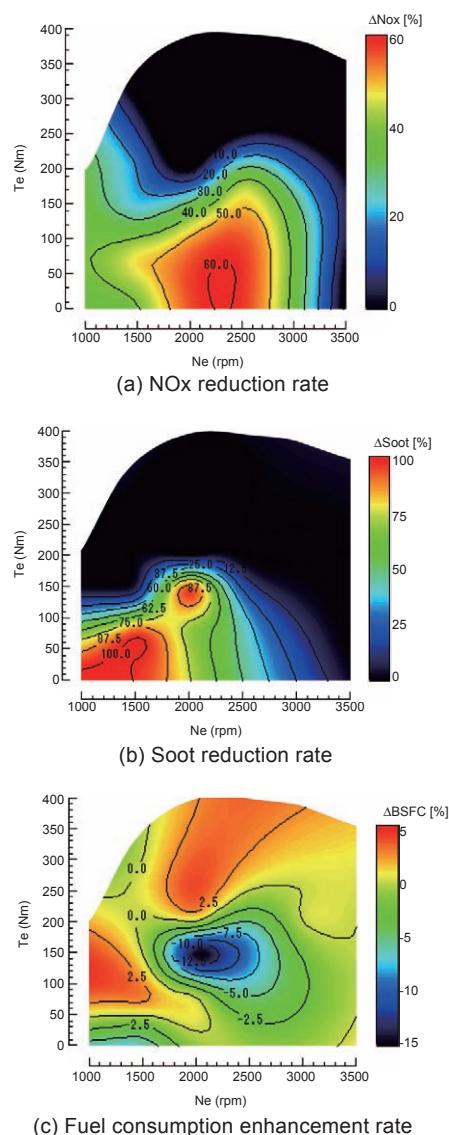


Fig. 18 Effect of PCCI combustion on emissions and fuel efficiency

low-speed, high-load range, the rate of reduction of soot emissions does not match that achieved in the high-speed, high-load range, but NOx emissions are reduced by approximately 30% against diffusive combustion.

In addition, while a decline in fuel efficiency can be observed in the high-speed, high-load range because the main injection timing has been retarded in order to control combustion noise, in the low-speed, low-load range, main combustion has been advanced due to the reduced speed of combustion, and this has resulted in increased fuel efficiency.

8. Conclusion

The following results were obtained in relation to the expansion of the range of application of PCCI combustion.

- (1) In order to expand the range of application of PCCI combustion, it is necessary to achieve an ignition delay and control the speed of combustion; the realization of increased EGR cooling performance and the use of a low compression ratio are effective means of achieving these goals.
- (2) In the low-speed, high-load range, in which it is challenging to control the speed of combustion due to restrictions on the introduction of EGR, the modification of combustion behavior through the use of closed pilot injection helped to enable the amelioration of the soot-NOx tradeoff with no increase in $dP/d\theta$ max.
- (3) The research indicated that the expansion of the range of application of PCCI combustion made it possible to expand simultaneous NOx and soot reductions to almost the entire operating range employed in FTP75 and NEDC modes during steady-state operation.

In future, looking towards the practical realization of the system, it will be necessary to develop real-time combustion control technologies for transient states.

References

- (1) Morita, T., Suzuki, N., Satoh, N., Wada, K., Ohno, H.: Study on low NOx emission control using newly developed lean NOx catalyst for diesel engines: SAE paper, 2007-01-0239 (2007)
- (2) Wada, K., Suzuki, N., Satoh, N., Morita, T., Yamaguchi, S., Ohno, H.: Study on emission-reducing method with new lean NOx catalyst for diesel engines: SAE paper, 2007-01-1933 (2007)
- (3) Murata, Y., Komiya, R., Kaneko, A., Daisho, Y., Suzuki, H., Ishii, H.: A study on the improvement of NOx reduction efficiency for a urea SCR system (Third report) -High NOx reduction efficiency mechanism at transient operation with low exhaust gas temperatures: JSAE paper, 20085846 (2008)
- (4) Kimura, S., Aoki, O., Kitahara, Y., Aiyoshizawa, E.: Ultra-Clean combustion technology combining a low-temperature and premixed combustion concept

- for meeting future emission standards: SAE paper, 2001-01-0200 (2001)
- (5) Akihama, K., Sasaki, S.: Mechanism of smokeless rich diesel combustion by reducing temperature: SAE paper, 2001-01-0655 (2001)
- (6) Kanda, T., Hakozaki, T., Uchimoto, T., Hatano, J., Kitayama, N., Sono, H.: PCCI operation with early injection of conventional diesel fuel: SAE paper, 2005-01-0378 (2005)
- (7) Kanda, T., Hakozaki, T., Uchimoto, T., Hatano, J., Kitayama, N., Sono, H.: PCCI operation with fuel injection timing set close to TDC: SAE paper, 2006-01-0920 (2006)

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