

Simultaneous Reduction of NO_x and Smoke by Divided Diffusion Combustion Using High Dispersion Staggered Layout Nozzle

Hirokazu ANDO¹Satoshi AOYAGI¹Masayuki NAKATSU¹Naoki OHYA, Ph.D.¹

ABSTRACT

In order to realize extremely low emissions with diffusive diesel combustion, a study was made of methods for smoke suppression under the high-boost, high-EGR conditions that are effective in reducing NO_x. Divided combustion that combines a reduction in the injected amount of main fuel with premixed combustion in which the amount of fuel injected early is increased was adopted in order to reduce the rich portion of the main diffusion combustion, which was the main generator of smoke in conventional combustion. The adoption of this divided combustion made it possible to raise the fuel injection pressure, which had previously been limited due to combustion noise, and a smoke reduction effect was confirmed together with the effect of divided combustion. In addition, a staggered spray layout was adopted in order to reduce dilution of the premixed injection. Combining these methods achieved diffusive diesel combustion with extremely low emissions, and reduced NO_x by 40% while not causing increases in combustion noise or smoke, or reduction of thermal efficiency relative to conventional combustion.

1. Introduction

As environmental controls on internal combustion engines grow ever more stringent, diesel engines with their characteristic higher efficiency are expected to contribute to CO₂ reduction. There is also a movement in European countries to ban the sale of vehicles with internal combustion engines from around 2030, and in this context, it has become urgent to keep pace with the strengthened controls on the emissions of the gas constituents of NO_x and PM that will be coming in the future. The cost involved in increasing the sophistication of systems for enhancing NO_x after-treatment capabilities, in particular, has become an issue. In order to simplify after-treatment systems, the smoke and feed NO_x emitted from the combustion chamber need to be reduced. In the technologies to enhance diesel combustion studied in the past, as typified by premixed charged compression ignition (PCCI) combustion⁽¹⁾, achieving low emissions involved one or more of reduced thermal efficiency, increased combustion noise, and increased oil dilution, making practical application

not readily achievable. The approach that was devised, therefore, was not to use premixed combustion for all combustion formats, but instead to use partially premixed combustion, which makes separate use of premixed combustion and diffusion combustion. Extensive research has been done on this approach, with varied results such as bi-modal combustion⁽²⁾, ZPCI-DI⁽³⁾, and so on. However, these research efforts face issues of in-cylinder combustion behavior and they have not yet achieved low emissions.

Table 1 shows the transitions of European emission regulations by year. European exhaust gas regulation introduced a real driving emissions (RDE) regulation with Euro 6.2. In addition, the European Commission is considering making its controls more stringent, for example by lowering the conformity factor (CF), which is a multiplier for determining allowable exhaust gas regulation values, to 1.0⁽⁴⁾. To support emissions regulations that are moving toward a CF of 1.0, there is demand for enhanced performance of NO_x after-treatment systems together with emission reduction technology for enhancement of combustion itself.

¹ Innovative Research Excellence Power Unit & Energy
E-mail: hirokazu_ando@jp.honda

Table 1 Transitions in emission regulations in Europe

	Euro 6.2 (6d-TEMP)	Euro 6.3 (6d)
Year of enforcement	2017-	2020-
Mode	WLTC and RDE	WLTC and RDE
NO _x regulation [mg/km]	80	80
NO _x CF	2.1	1.43

WLTC: Worldwide Light-duty Test Cycle

The purpose of the present research was to reduce NO_x in diffusive diesel combustion without decreasing thermal efficiency, or increasing combustion noise and smoke.

2. Conventional Combustion Issues

For emissions in diffusion combustion, both NO_x and smoke are determined by the concentration of air-fuel mixture in the flame portion of combustion and the combustion temperature. The concentration of air-fuel mixture is expressed by the equivalence ratio Φ . This is the value of the stoichiometric air-fuel ratio divided by the actual air-fuel ratio. The stoichiometric ratio of 1 is the boundary at which higher values indicate a rich air-fuel mixture and lower values indicate a lean air-fuel mixture. When a Φ -T map is used in the present research, soot that is particulate carbon matter is labeled as soot, while actual measurement results are obtained with a smoke meter, and are thus labeled as smoke. With regard to NO_x, the stoichiometric high-temperature portion in the vicinity of Φ 1 is the generation zone, and with regard to smoke, the rich portion at Φ 1.9 or higher is the generation zone. Typical measures to deal with emissions include NO_x reduction by lowering combustion temperature and smoke reduction by reducing the rich portion that accompanies homogenization of the spray.

The following shows the influence of these in conventional combustion together with the issues involved.

2.1. Issues Under High-boost, High-EGR Conditions

Lowering the combustion temperature is effective in reducing NO_x. Combustion temperature can be lowered by raising the boost pressure so as to keep Φ constant and increasing the EGR amount while maintaining the amount of air. An increase in the ambient pressure, however, is accompanied by a reduction in spray penetration so that the rich region grows, inviting an increase in smoke. This means that the trade-off between NO_x and smoke does not yield more than a certain enhancement when this approach is applied to conventional diesel combustion. In addition, it is apparent when multi-cylinder engines are taken into account that measures that involve raising the boost pressure will invite increased pumping loss due to the increased turbocharger work. This is yet another constraint on the margin of enhancement obtainable with the trade-off relationship between NO_x and smoke.

2.2. Issues Under High Fuel Injection Pressure

The measure of raising fuel pressure high for the purpose of spray homogenization by enhancing spray penetration can achieve a reduction of smoke. On the other hand, however, this invites an increase in NO_x, while the shortened combustion time also causes the heat release rate to rise sharply, which increases combustion noise. In conventional diesel combustion, therefore, the measure of raising fuel pressure high is limited by combustion noise.

2.3. Issues Under Premixed Injection Conditions

Premixed combustion by means of early injection as a measure to simultaneously reduce the rich region and the stoichiometric high-temperature portion is effective in enhancing the trade-off between NO_x and smoke. However, this invites an increase in heat loss and combustion noise due to pre-ignition as well as oil dilution due to adhesion of fuel on the liner. An increase in oil dilution also increases the frequency of oil maintenance and so needs to be kept as low as possible. For these reasons, it is no simple matter to address the conflicting relationship that exists from the decrease in thermal efficiency, reduction in user maintenance, and increase in combustion noise that occur with the reduction of NO_x and smoke in conventional diffusion combustion.

3. Formulating Targets and a Concept of Divided Combustion

3.1. Targets

As shown in Table 1, the target NO_x reduction rate is set by taking as a reference the feed NO_x of the 2018 model year i-DTEC engine⁽⁵⁾, which supports the Euro 6.2 standard of CF 2.1. When following the 2018 model year NO_x Storage Catalyst after-treatment system, in order to support the stricter regulation value of CF 1.0 in the future, it is estimated that the feed NO_x will need to be reduced by 50% or more. The target value for feed NO_x reduction rate was therefore set as 50% relative to the 2018 model year i-DTEC engine. Targets were also set for thermal efficiency, combustion noise, and smoke to maintain their same levels.

3.2. Simultaneous Reduction of NO_x and Soot

A new concept for reducing emissions was studied for the purpose of addressing the issues of conventional combustion.

Figure 1 shows the distribution of mass on the Φ -T map during main combustion. In order to reduce NO_x and soot simultaneously, their respective emission generation zones in the stoichiometric portion and the rich portion would need to be reduced. As explained earlier, with regard to the stoichiometric portion, the NO_x generation zone can be avoided and NO_x can be reduced by lowering the combustion temperature through higher boost and EGR. With regard to the rich portion, however, it is apparent that

the richer region with equivalence ratio of $\Phi 1.9$ or higher that appears during main combustion needs to be reduced in order to reduce soot. Higher fuel pressure cannot be adopted, however, since reducing the rich portion will increase NOx and combustion noise.

A method was therefore studied for lowering Φ in the main combustion portion and reducing the soot generation zone. Figure 2(a) shows the ratio to the crank angle of the region that is richer than $\Phi 1.9$, which is the soot generation zone. Conventional combustion is shown by the dotted line and the divided combustion concept by the solid line. Figure 2(c) shows Φ during main combustion by color distribution. Since combustion chamber space is limited near compression top dead center (TDC), high dispersion is needed, and with the same main injection fuel amount, reducing the rich region becomes an issue. Note that there

is an extensive unused space in the combustion chamber before TDC in Fig. 2(b), indicating that the rich region was lessened by reducing the main fuel amount during main combustion. It was thus decided to disperse the rich region by using that portion of the fuel amount to increase the pilot injection amount before TDC where there is extensive space. However, when the pilot injection amount is increased in the vicinity of TDC, there is concern that diffusion combustion caused by instantaneous ignition will result in an increase in the generation of NOx and soot. It was reasoned that in order to secure retarded ignition time, this needed to be combined with advancing the pilot injection timing. With a view to avoiding liner spray collision, which would invite oil dilution with the increased amount and advanced timing of pilot injection, a multi-staged approach may be effective in qualitative terms. It was on the basis of these approaches that we determined the concept of divided combustion.

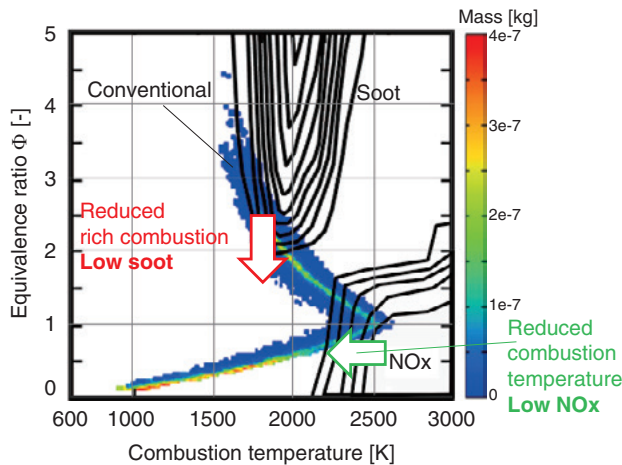


Fig. 1 Φ -T map during main combustion

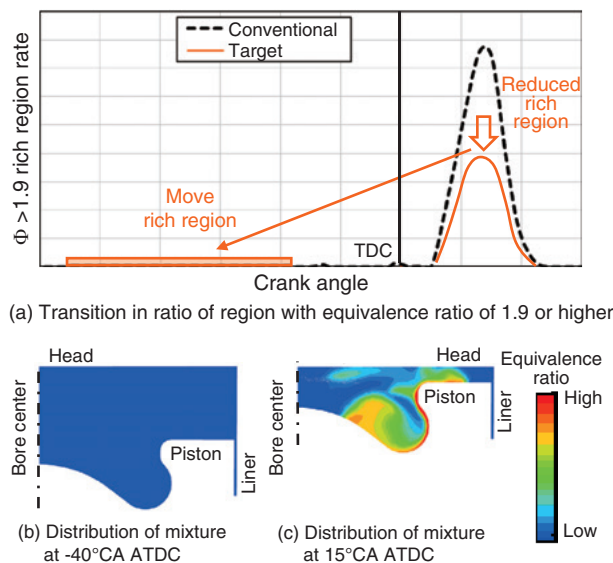


Fig. 2 Concept of rich region control

3.3. Support for Premixing

In the divided combustion concept, premixed combustion is implemented by means of early injection for the purpose of reducing the main injection amount. Oil dilution due to adhesion of fuel on the liner thus needs to be limited. In order to achieve the balance between premixed injection and main injection while maintaining spray penetration, while two injectors with differing specifications are thought to be needed, our goal was to achieve that balance with just one injector. In order to avoid adhesion of fuel on the liner exposed by early injection, four of the eight injector nozzle holes were directed downward. The remaining four nozzle holes were oriented as before, and those with different orientations were alternately arranged. The measure called staggered layout of injector nozzle holes⁽⁶⁾ is adopted for divided combustion in order to mitigate the liner adhesion of fuel by thus giving the nozzle holes separate orientations while the injector nozzle holes simultaneously yield a high dispersion effect.

4. Study of Specifications

4.1. Test Engine and Evaluation Load

Verification was conducted with a single-cylinder engine fabricated on the basis of the mass-production 1.6 L in-line four-cylinder specification. Table 2 shows the main specifications of the engine used in verification.

Figure 3 shows the emission mode load distribution in the envisioned vehicle. For the present research, the evaluation load point was set at the WLTC mode emission center point of 2000 rpm engine speed, 150 Nm engine torque, and 28.3 mg/st total fuel injection amount. All verification from this point forward was conducted at this evaluation load point.

The combustion noise level is considered to be represented by multiplying the structural response of the engine by the cylinder pressure, which is the source of

Table 2 Test engine specifications

Number of cylinders	1
Displacement volume [cm ³]	400
Bore [mm]	76
Stroke [mm]	88
Compression ratio	14.6, 16.1 (base)
Fuel injection system	Bosch CRI 2-25 (max. 250 MPa)
Injector	8 holes, 0.114 mm diameter
Fuel	EU spec diesel (sulfur < 10 ppm)
Boost device	Super charger

Table 3 Calculation method

CFD software	CONVERGE v2.4
Turbulence model	RNG k- ϵ
Spray model	Kelvin-Helmholtz and Rayleigh-Taylor
Combustion model	SAGE detailed chemical reaction
Chemical reaction	100 species and 432 reactions n-dodecane (with NO _x reaction)

vibration⁽⁷⁾. The combustion noise index (CNI) is a value based on the correlation between combustion noise and cylinder pressure in most internal combustion engines developed up to now. It is obtained by calculating the specific structural response and multiplying it by the measured cylinder pressure, and is an indicator that enables estimation of the combustion noise level from the cylinder pressure alone. This enables evaluation of the combustion noise level in a multi-cylinder engine, and even from a single cylinder. From this point forward, therefore, the CNI will be treated as the combustion noise index.

4.2. Calculation Method

The study of specifications was conducted using combustion simulation in addition to single-cylinder engine testing. CONVERGE version 2.4 was used for the computational fluid dynamics (CFD), and Table 3 shows an overview of the calculation method used. In calculating the combustion chemical reaction, the chemical reaction model by Wang et al. that adds the NO_x reaction to the n-dodecane mechanism⁽⁸⁾ was used. The engine specifications were made the same as for the test engine.

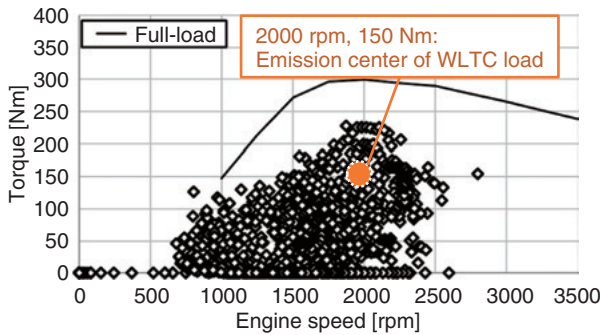


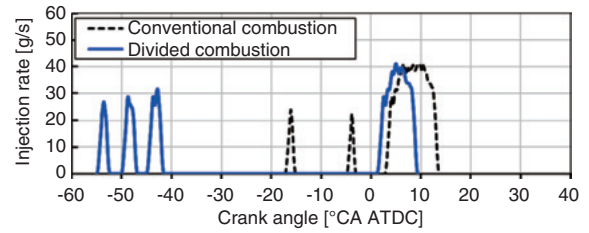
Fig. 3 Engine operation area in WLTC mode and evaluation load point

Table 4 Experimental conditions by premixed pilot injection amounts

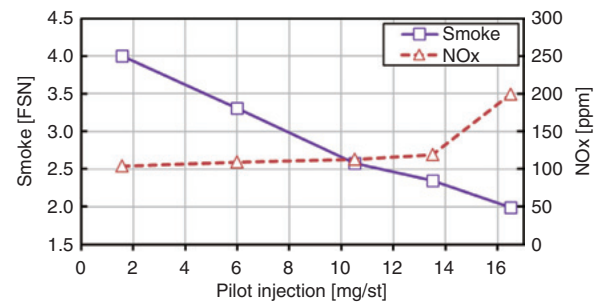
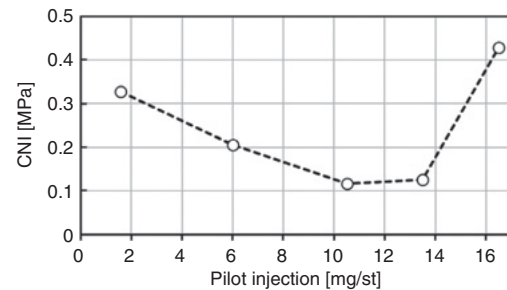
	Conventional combustion	Divided combustion			
Total injection [mg/st]	28.3	28.3			
Pilot injection [mg/st]	1.58	6.0	10.5	13.5	16.5
Pilot injection start timing [°CA ATDC]	-17.3	-55.0			
Number of pilot injection shots	2 shots	3 shots			

4.3. Demonstration of the Divided Combustion Concept

Demonstration of the divided combustion concept determined here was carried out. Table 4 shows the experimental conditions by premixed injection amount. Figure 4 shows the results from actual engine testing at the evaluation load point. The injection patterns shown in Fig. 4(a) have the same Φ , EGR rate, boost pressure, and fuel injection pressure. As shown in Fig. 4(b), increases in the pilot injection amount are accompanied by a reduction



(a) Injection rate


 (b) Smoke and NO_x


(c) CNI

Fig. 4 Effects of premixed pilot injection amounts

in smoke that is generated with main diffusion combustion as the major cause. In addition, the division of combustion causes a change in the pattern of heat release with respect to crank angle from a single peak to a double peak, and as the pressure amplitude decreases, the combustion noise is reduced as shown in Fig. 4(c), creating an extra margin with respect to the combustion noise target. Consequently, the fuel injection pressure, which had been limited by the combustion noise, can be raised to a high level. The optimal pilot injection amount that can simultaneously achieve smoke reduction, NO_x reduction, and combustion noise reduction is 10.5 mg/st. It was confirmed that when this is done, a 37% reduction in smoke is achieved with the same injection pressure as set for the conventional pilot injection amount.

With regard to the influence of the premixed injection timing, the experimental conditions are shown in Table 5 and the results from testing with an actual engine at the evaluation load point are shown in Fig. 5. Here, the pilot injection start timing shown in Fig. 5(a) has been changed, and the values for Φ , EGR rate, boost pressure, and fuel

Table 5 Experimental conditions by premixed pilot injection start timings

	Divided combustion				
Total injection [mg/st]	28.3				
Pilot injection [mg/st]	10.5				
Pilot injection start timing [°CA ATDC]	-60.0	-55.0	-50.0	-45.0	-40.0
Number of pilot injection shots	3 shots				

injection pressure are all the same. As shown in Fig. 5(b), advancing the premixed injection start timing helped ensure spray diffusion time for the pilot injection, and it is apparent that since enrichment is suppressed, smoke is reduced. The optimal pilot injection timing here was set to -55°CA ATDC, which can simultaneously achieve smoke reduction, NO_x reduction, and combustion noise reduction. This approach can realize higher fuel pressure without increasing combustion noise. The result is that spray penetration is increased under high boost, high EGR conditions and the rich portion is reduced, making it possible to reduce smoke.

4.4. Support for Premixed Injection

In the divided combustion concept, as staggered spray layout is adopted, a study was made of the spray layout in premixed injection. Figure 6 shows a comparison performed using CFD simulation between injection spray distribution in the cylinder with conventional pilot injection and with premixed pilot injection with a staggered spray layout. It is apparent that the spray from downward-pointing nozzle holes in a staggered layout shown in Fig. 6(b) limits liner contact.

The dilution that occurs at the evaluation load point in divided combustion with a conventional injector and

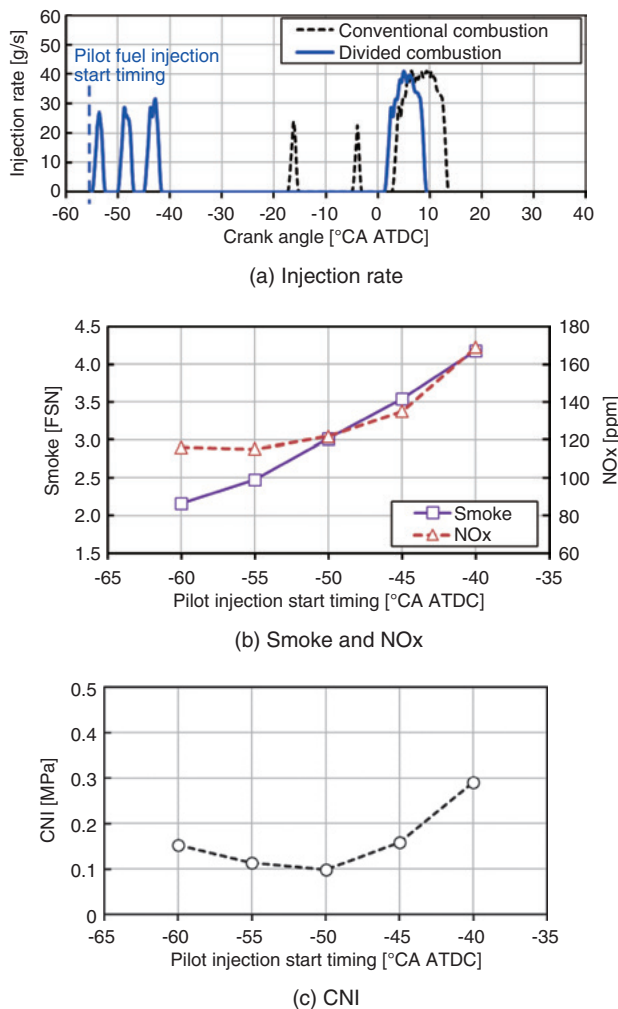


Fig. 5 Effects of premixed pilot injection start timings

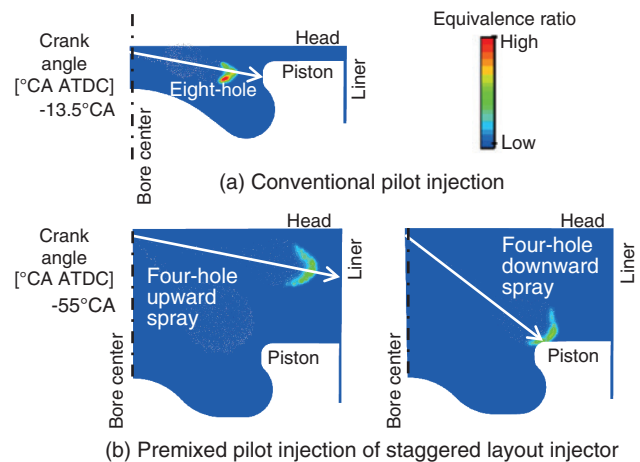


Fig. 6 Comparison of conventional pilot spray and premixed pilot spray with staggered layout injector

with a staggered spray layout was also estimated by CFD simulation. By staggering the layout of injector nozzle holes, the oil dilution that occurs when applying premixed injection was reduced by 24%.

At this point, actual measurements were made of oil dilution levels occurring in an actual engine with the injection timing and injection amount of pilot injection varied. Figure 7 shows the results for conventional spray and Fig. 8 shows the results with the staggered spray layout. This confirms that the oil dilution level has been lowered by the staggered spray layout relative to the conventional spray with the same pilot injection timing and amount. The staggered spray layout can thus be considered better than conventional spray with pilot injection that is early and in large amounts. These results were applied in setting the number of injection shots, the injection amount, and the injection timing with the staggered spray layout. The number of pilot injections was set at three, and the pilot injection amount and timing were set to 2.5 mg/st at -55°CA ATDC, 3.5 mg/st at -50°CA ATDC, and 4.5 mg/st at -45°CA ATDC.

Together with the above, verification was also carried out of the after-treatment combustion mode that performs post-injection with the staggered spray layout. The after-treatment combustion mode causes spray adhesion to the sleeve from post-injection in the expansion process. Since the use of a staggered spray layout can reduce the dilution during post-injection, it was confirmed by CFD simulation that dilution can also be reduced in the case of the after-

Table 6 CFD conditions of divided combustion

	Conventional combustion $\varepsilon 16.1$	Divided combustion $\varepsilon 14.6$
Fuel injection pressure [MPa]	140	200
Boost pressure [kPa_abs]	172	182
Equivalence ratio	0.81	0.81
EGR rate [%]	28.0	32.0
Pilot injection [mg/st]	1.58	10.5
Pilot injection start timing [$^{\circ}\text{CA}$ ATDC]	-17.3	-55.0
Number of pilot injection shots	2 shots	3 shots

treatment combustion mode. These observations made it possible to help prevent an increase in the frequency of oil maintenance under the divided combustion concept.

4.5. Main Diffusion Combustion

Having implemented divided injection and adopted the staggered spray layout, a downward spray flow is added in main diffusion combustion that differs from the conventional flow, and its influence was confirmed. Although the compression ratio is lower than in the conventional combustion chamber where ε is 16.1, a combustion chamber with ε 14.6 was devised for divided combustion that secures the greatest combustion chamber volume for the staggered flow, and the transition in

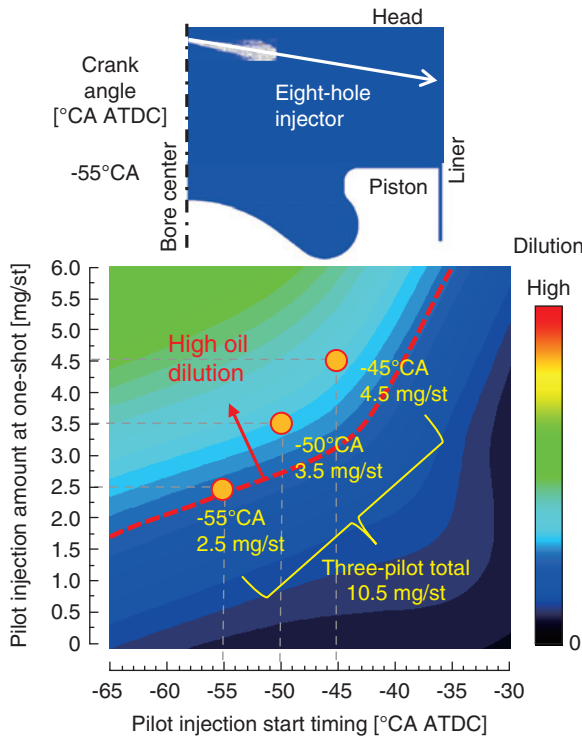


Fig. 7 Oil dilution level of one-shot pilot injection with conventional injector

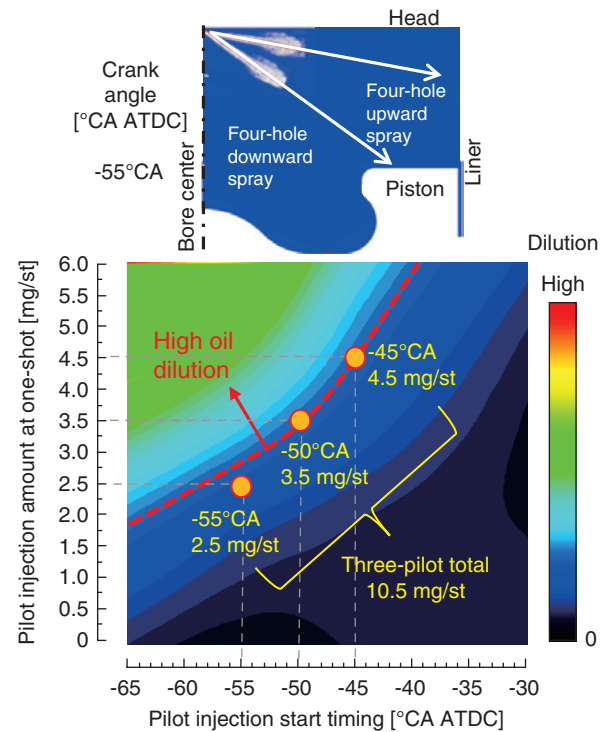


Fig. 8 Oil dilution level of one-shot pilot injection with staggered layout injector

distribution of equivalence ratio was verified by CFD simulation.

The divided combustion with its higher boost, higher fuel pressure up to the allowable combustion noise, and application of the staggered spray layout is shown in comparison with conventional combustion. Table 6 shows the conditions at the evaluation load point for study by CFD simulation. Figure 9 shows the transitions in ratio in the region where Φ is 1.9 or higher, and Fig. 10 shows maps

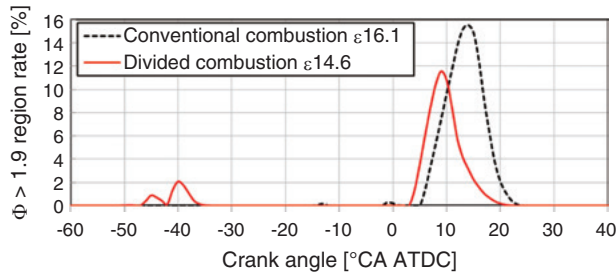


Fig. 9 Transitions in ratio in region with equivalence ratio of 1.9 or higher

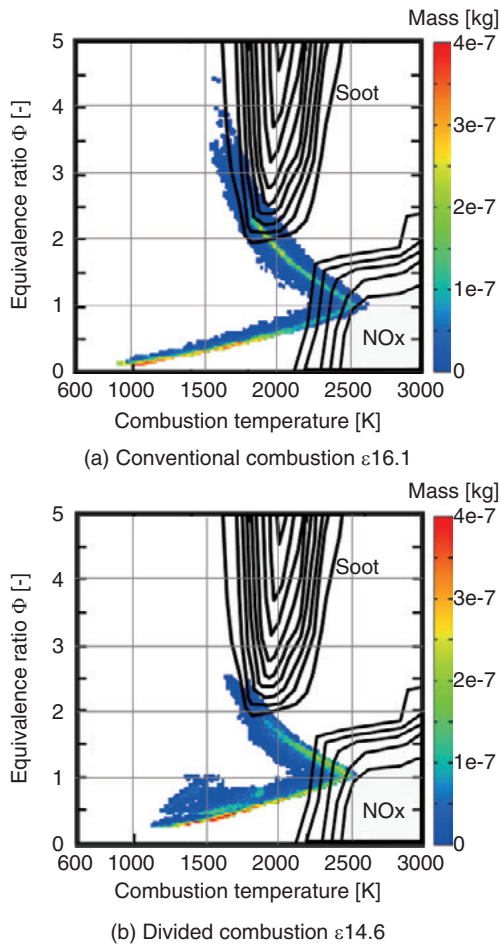


Fig. 10 Φ -T maps of conventional combustion and divided combustion during main combustion

for Φ -T during main combustion. In the divided combustion specification with ε of 14.6, the effects of reducing the main injection amount, raising fuel pressure higher, and having the staggered spray layout yield a reduction in the rich portion of main combustion. It can be confirmed by CFD simulation that as a result, the soot generation zone is successfully avoided, as was the aim of the initially formulated concept of divided combustion.

Attention was also focused on the main combustion, which has a large influence on smoke emission. Figure 11 shows the equivalence ratio distribution isosurfaces for the region with Φ of 1.9 or higher. A check of the equivalence

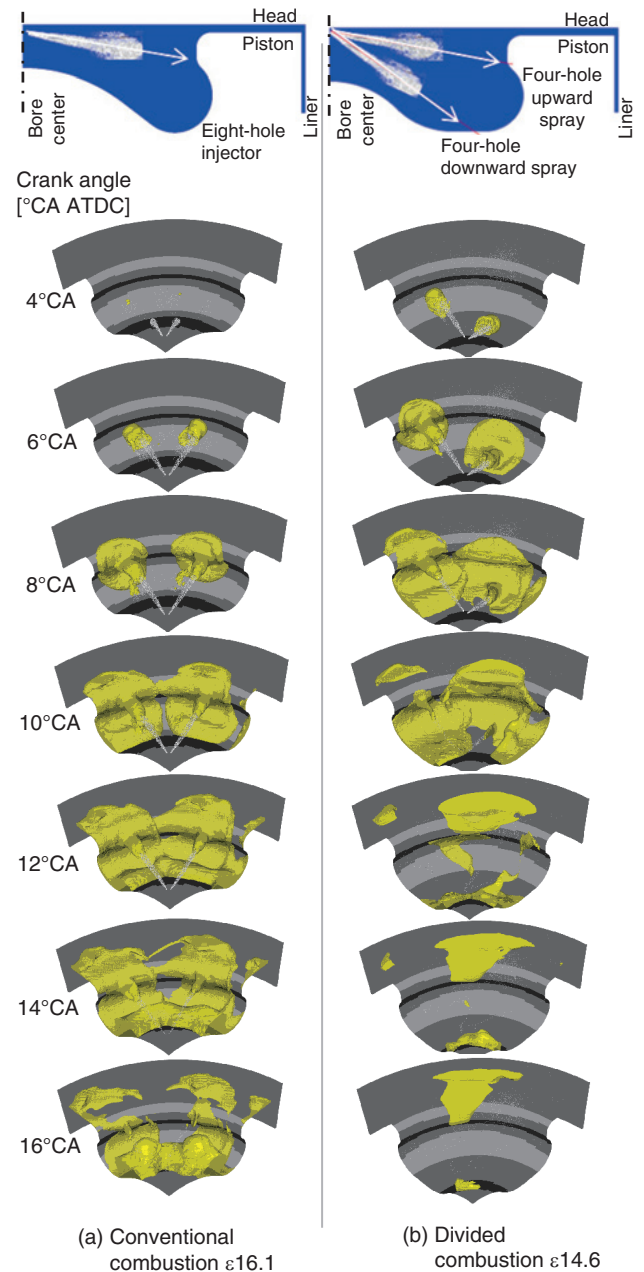


Fig. 11 Isosurfaces for region with equivalence ratio of 1.9 or higher during main combustion

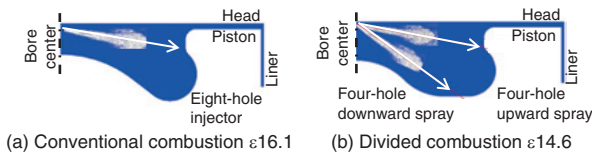
ratio distribution isosurfaces makes it possible to confirm that by comparison with conventional combustion, the divided combustion specification with ε of 14.6 has achieved reduction of the main injection amount due to divided combustion, and this in combination with the effect of higher fuel pressure reduces the volume of the rich portion in the latter part of main combustion from the crank angle of 12°CA ATDC on. Due to the adoption of the staggered spray layout, in particular, interference from adjoining sprays in the combustion chamber no longer occurs, contributing to the reduction in the volume of the rich portion.

5. Results of Verification with Single-cylinder Engine

Verification was carried out under high-boost, high-EGR conditions in the single cylinder of an actual engine embodying the divided combustion concept with the ε 14.6 specification that applied divided injection and the staggered spray layout. Regarding the higher boost amount, an upper limit of 10 kPa was set to the rise in boost pressure so that pumping loss would not be increased by the greater turbocharger activity involved when a multi-cylinder engine is used.

Figure 12 shows the experimental conditions at the evaluation load point for a conventional combustion specification and divided combustion specification with ε of 14.6. Figure 13 shows the injection rate and heat release rate. With the injection pattern shown in Fig. 13(a) in the divided combustion specification with ε of 14.6, the application of divided combustion consisting of premixing and diffusion causes the pressure amplitude to be divided in half, as can be observed from the heat release rate shown in Fig. 13(b).

Figure 14 shows the CNI. The division of the pressure amplitude causes the CNI to decrease from 0.16 MPa to 0.11

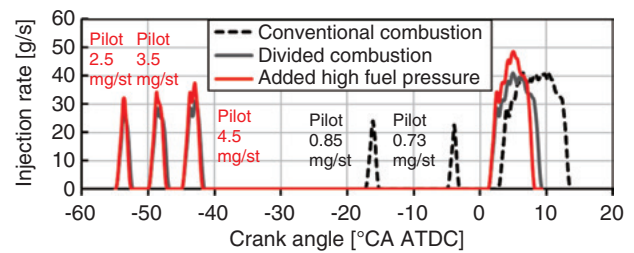


	Conventional combustion base ε 16.1	Divided combustion base ε 14.6	Added high boost pressure	Added high fuel pressure	Added high EGR rate
Fuel injection pressure [MPa]	140	140	140	200	200
Boost pressure [kPa_abs]	172	172	182	182	182
Equivalence ratio	0.81	0.81	0.81	0.81	0.83
EGR rate [%]	28.0	28.0	32.0	32.0	34.0

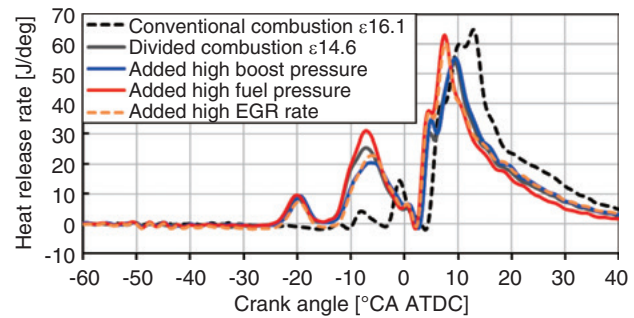
Fig. 12 Experimental conditions of conventional combustion and divided combustion

MPa in divided combustion. In conventional combustion, there is no extra margin with regard to the combustion noise target, but in divided combustion, the combustion noise can be held within the target value even when the boost, fuel pressure, and EGR are raised higher.

Figure 15 shows smoke, NO_x, and thermal efficiency in conventional combustion and in the divided combustion specification with ε of 14.6. A comparison with conventional combustion from the smoke and NO_x emission amounts shown in Fig. 15(a) indicates that divided combustion can reduce smoke by 47% by means of higher boost and fuel pressure, and that combining these with higher EGR makes it possible to reduce NO_x emission by 40%, which approaches the emission target, with the same amount of smoke. This can be considered



(a) Injection rate



(b) Heat release rate

Fig. 13 Injection strategy and heat release rate of conventional combustion and divided combustion

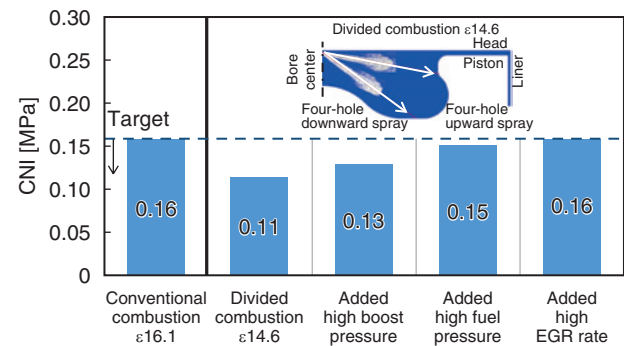


Fig. 14 CNIs of conventional combustion and divided combustion

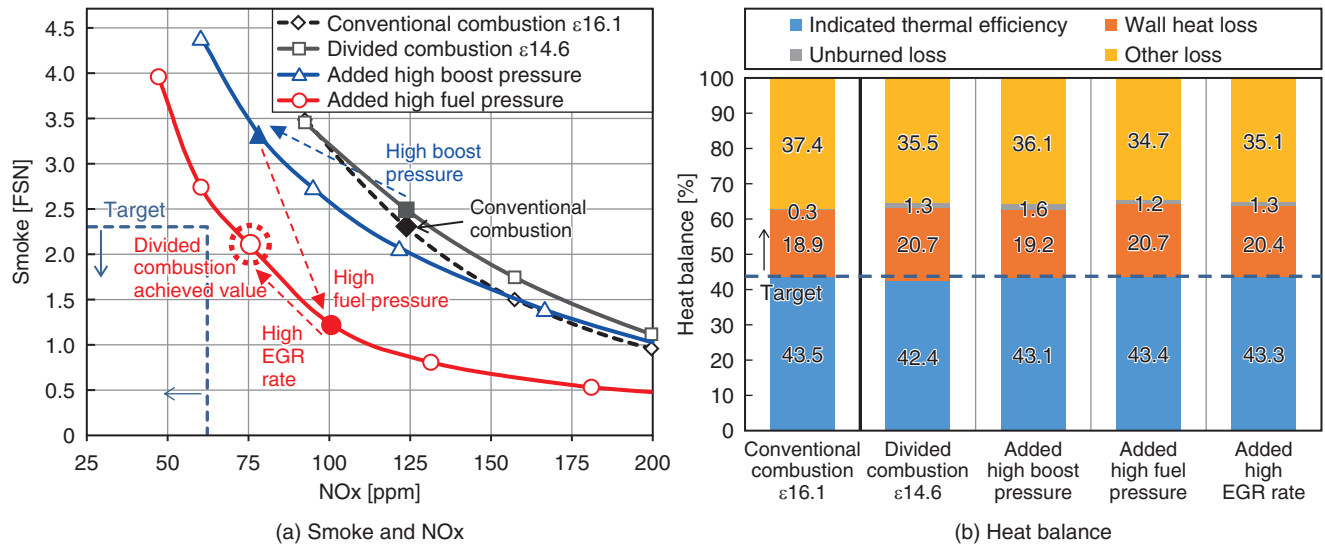


Fig. 15 Smoke and NOx and thermal efficiency of conventional combustion and divided combustion

to have obtained the reduction in the rich portion of main combustion by the effects of reducing the main injection amount, raising fuel pressure, and adopting the staggered spray layout, as was the aim of the initially formulated concept of divided combustion. It is also the case with thermal efficiency, as shown in Fig. 15(b), that while the adoption of premixed combustion increases wall heat loss, the wall heat loss is also mitigated by the effect of lowered combustion temperature that comes from the higher boost and EGR in divided combustion. As a result, where the target is 43.5%, the indicated thermal efficiency recovers to 43.3%, and this can be considered equal to the target level.

These results from verification in an actual engine indicate that the divided combustion specification with ε of 14.6 has achieved a 40% reduction in NOx emissions relative to conventional combustion, which closely approaches the emission target, while retaining the same levels of indicated thermal efficiency, smoke, and combustion noise.

6. Conclusion

The introduction of the divided combustion concept with application of the staggered spray layout yields a higher dispersion effect than the conventional specification. This achieved a 40% reduction in NOx emissions while retaining the indicated thermal efficiency, smoke, and combustion noise at the same levels with the evaluation load point at 2000 rpm engine speed, 150 Nm engine torque, and 28.3 mg/st total fuel injection amount. The findings obtained are given in the following.

(1) The divided combustion approach was devised as a combination with premixed combustion by early injection with the aim of reducing the fuel injection amount under high-boost, high-EGR conditions in main

diffusion combustion, which was the major generator of smoke in conventional combustion. It was confirmed that this approach reduced smoke by 37% relative to conventional pilot injection with the same fuel injection pressure.

- (2) The adoption of divided combustion successfully reduced combustion noise by 30%, enabling a 60-MPa increase in the fuel injection pressure that had formerly been limited by combustion noise. The effect of divided combustion together with the high dispersion effect of the staggered spray layout was confirmed to reduce smoke by 47%. This, in addition to the combination with higher EGR, achieved a 40% reduction in NOx with the same level of smoke.
- (3) The adoption of the staggered spray layout yielded a 24% reduction in the dilution occurring in premixed injection, making it possible to help prevent an increase in the frequency of oil maintenance.

Going forward, there appears to be a reasonable possibility that NOx emissions can be further reduced by changing the combustion chamber shape to suit divided combustion, raising EGR even higher, and other such means.

References

- (1) Hatano, J., Harada, T., Matsui, K., Kobayashi, H., Matsui, R.: Research on Expansion of Premixed Charge Compression Ignition (PCCI) Diesel Combustion Operation Range, Honda R&D Technical Review, Vol. 22, No. 2, p. 123-130
- (2) Inaba, K., Zhang, Y., Sang, W., Del Lucia, B., Kobashi, Y., Shibata, G., Ogawa, H.: Improvement in Semi-premixed Diesel Combustion with Suppression from Interference of Primary Premixed Combustion to

- Secondary Fuel Spray, 2020 JSAE Congress (Autumn) Proceedings, No. 113-20, (2020) (in Japanese)
- (3) Pan, W., Yokoyama, T., Bao, Z., Horibe, N., Kawanabe, H., Ishiyama, T.: Effects of Fuel Properties on Combined PCCI and Conventional Diesel Combustion, 2019 JSAE Annual Congress (Spring) Proceedings, No. 65-19, (2019)
- (4) European Parliament: Amendments on the proposal for a regulation of the European Parliament and of the Council amending Regulation (EC) No 715/2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, (2020)
- (5) Komatsu, N., Yano, H., Kitayama, N., Yamaya, Y., Shuto, Y., Takahara, R.: Development of the New 1.6L Diesel Engine Compliant to RDE, 2018 JSAE Congress (Autumn) Proceedings, No. 120-18, (2018) (in Japanese)
- (6) Koto, F., Mori, K., Kubo, K., Senda, J., Fujimoto, H.: Fundamental Study on Fuel Spray Characteristics of High Dispersion Nozzle (Staggered Layout Nozzle), Atomization, Vol. 13, No. 44, p. 1-7, (2004) (in Japanese)
- (7) Torii, K.: A Time Domain Analysis Method to Estimate the Contributions of Engine Radiation Noise Components Using Multiple Regression Analysis, Transactions of Society of Automotive Engineers of Japan, Vol. 44, No. 4, p. 1051-1057, (2013) (in Japanese)
- (8) Wang, H., Ra, Y., Jia, M., Reitz, R. D.: Development of a reduced n-dodecane-PAH mechanism and its application for n-dodecane soot predictions, Fuel, Vol. 136, p. 25-36, DOI 10.1016/j.fuel.2014.07.028, (2014)

■ Author ■



Hirokazu ANDO



Satoshi AOYAGI



Masayuki NAKATSU



Naoki OHYA