



Special Review

Review

Research History of High-speed, Direct-injection Diesel Engine Combustion Systems for Passenger Cars

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■**ABSTRACT** High-speed direct-injection diesel engines applied to passenger cars since the second half of 1980's have been making great strides through several stages in all of power, exhaust emissions, and noise, vibration and harshness under keeping high thermal efficiency, especially since appearances of common-rail (CR) injection system and high-boost-pressure supercharging systems in 1990's. At each stage, our laboratories played some key roles in clarifying in-cylinder phenomena and indicating directions and measures for further improvement, such as clarifying high-pressure fuel injection effect, multiple-injection effect and its optimization, development direction of the modern combustion system consisting of the CR injection system and shallow-dish-type combustion chamber, effect of combining high-boost-pressure, high exhaust-gas-recirculation rate and extremely high injection pressure, alternative combustion systems of "dual-fuel stratified PCCI" and "quiescent" combustions, and so on. In this review, the evolution history of diesel-engine combustion systems for passenger cars is outlined, and then results of the above-listed subjects together with a useful numerical-simulation tool for engine planning and control-parameters adjusting are all introduced.

■**KEYWORDS** Direct-injection Diesel Engine, Combustion System, Passenger Car, In-cylinder Analysis, Optically Accessible Single-cylinder Engine, Numerical Simulation

1. Introduction

Diesel engines originally have the highest thermal efficiency among internal combustion engines and also high torque at medium and low engine speeds, and therefore have been widely used in trucks and buses worldwide since 1940's. On the other hand, the number of diesel-powered passenger cars was limited until the middle of 1990's, mainly due to both exhaust emissions, especially black smoke, and large noise, vibration and harshness (NVH).

Since the second half of 1990's, however, not only the performance but also the exhaust emissions and NVH of high-speed diesel engines for passenger cars have been greatly improved through several stages, due primarily to the appearance of common-rail injection systems, high-efficiency aftertreatment systems, and the remarkable advance of turbochargers and electronic control systems. At each stage of the above-mentioned evolution of high-speed diesel engines, our laboratories played some important key roles both in clarifying in-cylinder phenomena on the exhaust emissions, NVH and fuel economy with

various originally-developed analysis methods, and in indicating the direction and measures for further improvement. Hereinafter, the evolution history of diesel engine combustion systems for passenger cars is outlined and then the major research results obtained in our laboratories are introduced.

2. Evolution History of Diesel Engine Combustion Systems for Passenger Cars

2.1 First-stage Diesel Engines for Passenger Cars

The indirect injection (IDI) combustion system with a sub combustion chamber was originally used for passenger-car diesel engines, because good fuel-air mixing was achieved by very high-speed swirl flow generated in the sub chamber so that high-speed operation was possible even with a simple fuel injection equipment, and also somewhat low level of exhaust emission was realized. On the other hand, heat loss from in-cylinder gas to combustion chamber wall was large, leading to relatively low thermal efficiency and limitation in increase of power density

due to the high thermal load. In addition, further reduction of exhaust emissions corresponding to the next generation, stringent emission regulation was essentially difficult in the IDI diesel engine.

2.2 Shift in Combustion Systems from IDI to DI

In order to solve the above-mentioned problems, in the second half of 1980's, shift in combustion systems from the IDI type to a direct injection (DI) type began in passenger-car diesel engines, which opened a door of the age of high-performance and good fuel-economy diesel engines. At the first stage, however, the high-speed DI (HSDI) diesel engines were equipped with a jerk-type injection system and a large hole-diameter nozzle, leading to large NVH and insufficiently low exhaust emissions. Therefore, at this stage, diesel-powered passenger cars did not spread widely.

2.3 Appearance of DI Diesel Engines with Common-rail Injection System

In the same age, the second half of 1980's, a common-rail (CR) injection system was first developed by Denso Corporation. In the conventional jerk-type injection system, fuel can be injected only at about compression top dead center (TDC) and injection pressure depends on engine speed and load (i.e. injected fuel quantity). On the other hand, in the CR injection system, multiple fuel injections at any timing during compression and expansion strokes are possible and injection pressure can be set independently of engine speed and load. In addition, the CR injection system had higher peak injection pressure of 145 MPa.

Responding to this innovation of fuel injection equipment (FIE), in the second half of 1990's, HSDI diesel engines with the CR injection system (CR-HSDI diesel engines) were developed and used for passenger cars. These engines, assisted by sophisticated turbochargers such as a variable-nozzle-turbine (VNT) turbocharger, had high power and torque densities of about 50 kW/L and 145 Nm/L, respectively, which were sufficient for normal driving in passenger cars. In addition, with the multiple fuel injections, the NVH levels decreased to levels comparable with those of gasoline-powered cars, and also exhaust emissions reduced drastically. Furthermore, the maximum brake thermal efficiency reached 42 to 43% and fuel economy

under actual driving conditions was excellent. Thus, at this stage, diesel-powered passenger cars widely spread in all the classes including premium cars.

2.4 Remarkable Increase in Power and Torque Densities

In the middle of 2000's, performance of CR-HSDI diesel engines was remarkably improved mainly owing to advanced supercharging technology such as a two-stage turbocharger system. In these engines, power and torque densities reached 65 kW/L and 185 Nm/L, respectively. In addition, peak-torque range was furthermore expanded from 1,500 rpm to about 3,000 rpm, and also torque under higher engine speeds were kept to be high value such as 70 to 80% of peak torque at 4,500 rpm and still 60% at 5,000 rpm. These characteristics were sufficient for emotionally sporty driving.

In addition to the power increase, good fuel economy was kept by reducing losses of friction and heat flux to walls, and NVH level was further improved mainly by the evolution of CR FIE such as increased number of multiple injections and higher peak injection pressure up to 180 MPa. Exhaust emission levels were also further reduced with the evolved CR FIE, thermal management and high efficient aftertreatment systems of diesel particulate filter (DPF) and advanced catalysts such as a nitrogen oxides (NOx) storage reduction (NSR) catalyst, a selective catalytic reduction catalyst with reducing agent of urea (Urea-SCR), and so on.

2.5 Two Main Streams of Diesel Engine Development

Since the last stage of 2000's, diesel engines newly developed were classified into two categories. One is the downsized diesel engine with remarkably high power and torque densities, and the other is the cost-effective diesel engine with both necessary performance for practical use and good fuel economy. Both types are outlined as follows.

2.5.1 Engine Downsizing Based on Further Increase in Power and Torque Densities

Since around 2010, power and torque densities of CR-HSDI diesel engines have been increasing up to 93 kW/L and 247 Nm/L, respectively, owing to

further advance in supercharging technology such as two-stage supercharging systems with double or triple turbochargers and decreased loss of air path systems, and also further evolution in CR FIE such as furthermore increased number of multiple injections and peak injection pressure up to 250 MPa. In addition, a new combustion technique, that is, combination of high boost-pressure charging, high exhaust-gas-recirculation (EGR) rate and the very high injection pressure led very low engine-out exhaust emissions even under medium and high load conditions. This technique enabled drastic engine downsizing such as a shift from 8-cylinder engines with displacement volume of 4.0 L to 6-cylinder with 3.0 L. The engine downsizing really contributed to reduction in engine weight and size and improvement in car-based fuel economy.

2.5.2 Cost-effective and High-efficiency Diesel Engines

The above-mentioned highly-downsized diesel engines require high-cost components such as the high-boost-pressure supercharging system, high-class CR FIE, structural parts of high-class material for sustaining the high in-cylinder pressure and thermal load and so on, leading to increase in engine cost. Thus, there is the other trend to develop cost-effective diesel engines without downsizing which have sufficient power and torque for normal driving and good fuel economy under actual driving conditions. These engines are suitable to popular-edition cars.

3. Researches on Combustion System for Each Generation Diesel Engine Conducted in Our Laboratories

3.1 Effects of High-pressure Fuel Injection on Combustion and Exhaust Emissions

At the stage of the shift in diesel combustion systems from IDI to DI

described in Section 2.2, usage of high pressure fuel injection was the most important key item for realizing the HSDI diesel engines applicable to passenger cars. Concretely speaking, what should be understood were fuel injection pressure effects on combustion and exhaust emissions and also mechanisms of the effects, and then desired specifications of the FIE and main components of the combustion system.

Responding to this requirement, researches on the effect of fuel injection pressure and also injection rate were conducted by using a conventional jerk-type FIE and a pioneering prototype CR FIE supplied by Denso. In these studies,⁽¹⁻⁴⁾ a special single-cylinder diesel engine with wide observation area shown in **Fig. 1** and diesel fuel with an additive of copper oleate for visualizing non-luminous flames were both used, and high-speed direct photography and two-color pyrometry method⁽⁵⁾ were applied for analyzing the in-cylinder phenomena such as fuel spray behavior, flame development process, flame temperature, and so on. As a result, the following points were clarified.

(1) As shown in **Fig. 2**, increase in injection pressure remarkably reduces smoke (i.e. particulate), but, in this case, the effect is saturated at injection pressure of about 100 MPa.

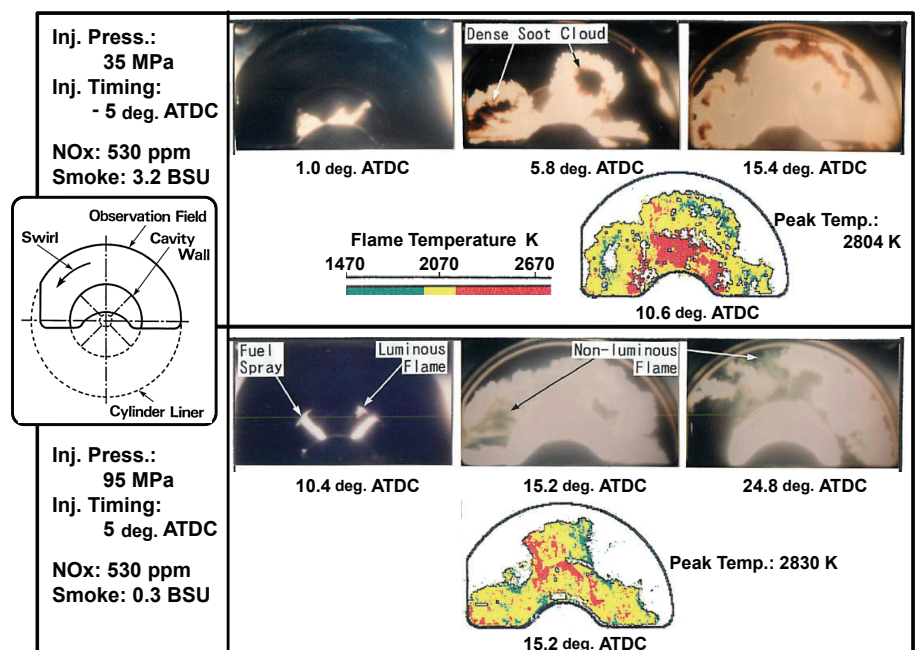


Fig. 1 Effect of fuel injection pressure on flame development under the same exhaust NOx condition.

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(2) Increasing injection pressure leads to the following phenomena.

(a) Ignition delay is shortened (Fig. 2) and ignition position shifts from the vicinity of nozzle tip to that of piston cavity wall (Fig. 1). This shift prevents the spray from being wrapped by flame and thus ensures air entrainment into the spray.

(b) Luminous flames (diffusion flames) are reduced and non-luminous flames (premixed flames) shown as the green flame areas in Fig. 1 appear, which corresponds to the accelerated mixture formation.

(c) Both combustion period and lifetime of the luminous flame are shortened, but those effects are saturated also at about 100 MPa in this case (Fig. 2).

(3) Heightening injection pressure up to about 100 MPa increases NOx emission in this case. The increase in NOx is caused not by increase in peak flame temperature but by enlargement of high-temperature (for example, over 2,170 K) flame region.⁽³⁾

This study led to the above-described results was a pioneering work and indicated the development direction.

3. 2 Optimization of Multiple Injection Patterns and Its Effects on Combustion and Exhaust Emissions

At the stage of the development of CR-HSDI diesel engines described in Section 2. 3, clarifying the usage of multiple fuel injections was the most important key item, because various multiple injection patterns tried at the first stage led to very puzzled results such as unexpected, worsened exhaust emissions, lubricating oil dilution, and so on.

Responding to this problem, studies to clarify the effects of multiple fuel injections and the mechanisms were conducted by using two optically-accessible, single-cylinder engines; one is the same engine as that used in Section 3. 1 and the other is a modern one with four valves and a centrally-located injector.⁽⁷⁾ In these studies,^(6,7) a high-speed color shadowgraph photography were additionally applied for analyzing the in-cylinder phenomena. Some of the concrete problems tackled in these studies and also obtained results and solutions are as follows.

3. 2. 1. Close-pilot Injections

A small-quantity fuel injection just before main injection is called “close-pilot injection”, which effectively reduced combustion noise, fuel consumption and NOx emission, but was apt to remarkably increase exhaust smoke in complicated manners depending on pilot fuel quantity, interval between pilot and main injections, main-injection timing, and so on. Thus, it was very difficult to properly utilize the close-pilot injection. The analysis results and solution from our study⁽⁶⁾ are the followings.

(1) In the cases of high exhaust smoke level shown in the left- and right-columns of Fig. 3, pilot flames formed prior to main injection are conveyed by swirl flow and

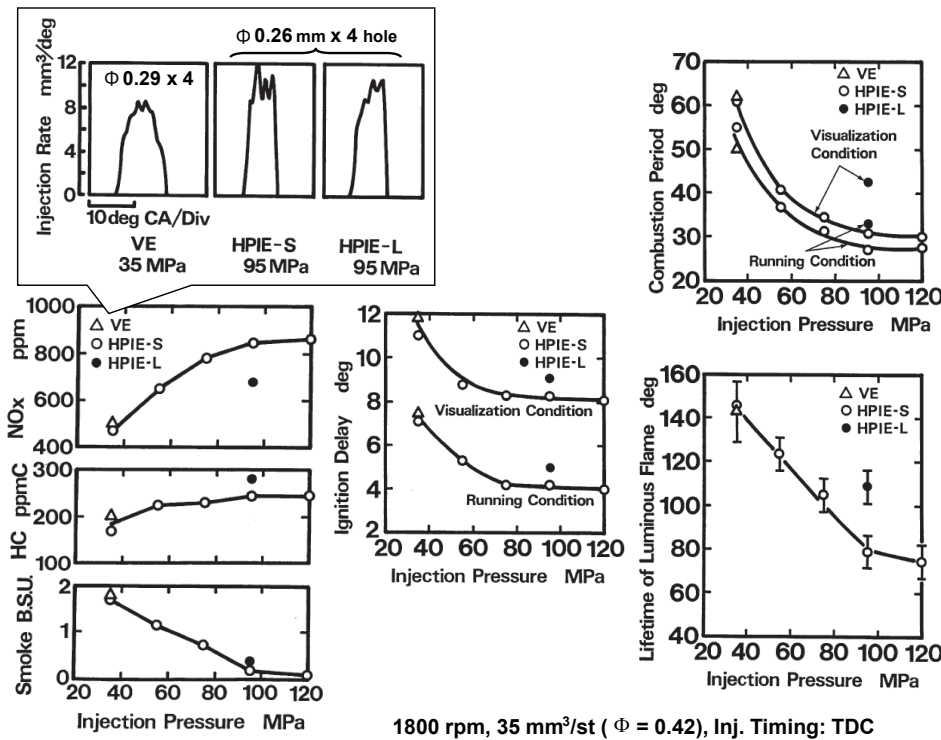


Fig. 2 Effect of injection pressure on exhaust emissions and combustion characteristics.

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located just ahead of downstream main-injection sprays so that the main sprays enter into the pilot flames and are fully wrapped by flames. This leads to insufficient air entrainment into the main spray and therefore formation of large amount of soot, resulting in the high smoke. This is caused by excessively long pilot-main interval and large fuel quantity of pilot injection (the left-column case), and also by excessively long ignition delay of main-injection fuel due to the far-retarded injection timing (the right-column case). Additionally, soot formation is promoted by poor atomization of pilot fuel due to throttling effect at the nozzle seat.

(2) Excessive fuel quantity of pilot injection also causes increase in NOx, because excessively large pilot flame is generated and thus becomes a source of NOx and also accelerates the combustion of main-injection fuel. (3) Consequently, shorter pilot-main interval and smaller quantity of pilot fuel, whose optimum values depend on swirl level and ignition delay, and also use of small-orifice-diameter nozzles are all essential. With optimizing these factors, each pilot flame is adequately small-scaled and is located slightly downstream of each main spray, which prevents the main sprays from being enveloped by flames, leading to low smoke as shown in the middle column case of Fig. 3.

3. 2. 2 Early-pilot Injections

A small-quantity fuel injection far before main injection is called “early-pilot injection”, which also had the potential to effectively decrease combustion noise and NOx with scarcely increased smoke and to additionally increase low-speed full torque, but was apt to deteriorate hydrocarbon (HC) emission, fuel consumption and reduction rate of combustion noise at light loads.⁽⁷⁾ Lubricant oil dilution by fuel adhesion to cylinder wall was also a problem. In this study,⁽⁷⁾ a special apparatus for detecting the adhered fuel state and quantity shown in Fig. 4 were used. The analysis results and related findings are as follows:

(1) Double early-pilot injection, that is, two injections with an interval of about 20 deg. CA and each fuel quantity of about half of that in the original single-pilot injection, effectively suppressed the increases in HC and fuel consumption, and effectively reduced combustion noise. These effects result from that the double-pilot injection increases burnt amount of the pilot fuel before main-injection start due to less fuel adhesion to cylinder wall, which increases in-cylinder gas temperature and thus shortens ignition delay of the main-injection fuel. Through measuring weight of the adhered fuel with blotting paper, it

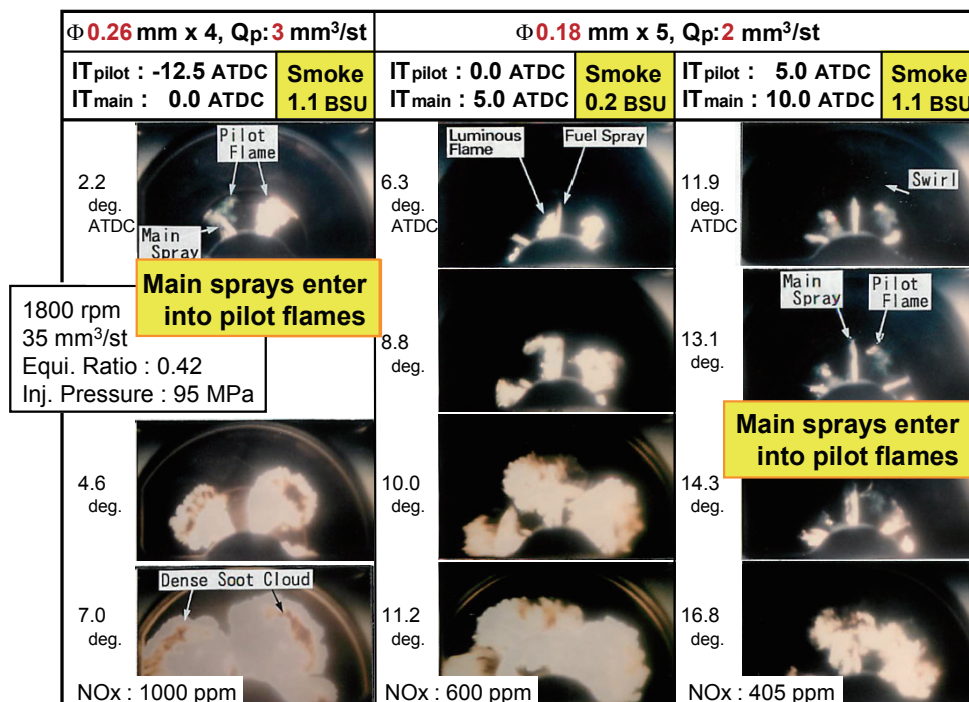


Fig. 3 Effect of close-pilot injection on combustion and exhaust smoke.

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was quantitatively confirmed that the adhered fuel quantities were reduced by about 50% or more with double early-pilot injections.

(2) Fuel quantity adhered to cylinder wall had been naturally thought to decrease with reduced fuel quantity and lowered injection pressure of the pilot injections, due to decreased spray-tip penetration. However, in reality, the fuel adhesion to cylinder could be prevented only with moderate quantity and injection pressure of the pilot fuel, as shown in Fig. 4. This is because excessively small fuel quantity and/or low injection pressure cause excessively low real injection pressure at nozzle exit due to promoted throttling effect at the nozzle seat, so that very large fuel droplets are formed and reach the cylinder wall.

3. 2. 3 After Injections

A small-quantity fuel injection just after main injection is called “after injection”, which effectively decreased smoke, HC and fuel consumption only with adequate main-after interval of about 5 deg. CA and after-injection quantity of about 2 mm³. Mechanism of the dependence on the interval and quantity should have been clarified for widely applying the after-injection technique. The analysis results in this study⁽⁷⁾ are as follows:

(1) In-cylinder observation, picture processing and computational fluid dynamics (CFD) analysis clarified that jet flame of the after injection catches and oxidizes the soot previously formed in the squish area, due to

the raised temperature and enhanced mixing with surrounding air. Excessive fuel quantity of after injection generates soot by itself and excessively long main-after interval prevents the after-injection flame from catching the remaining soot.

(2) Another problem of NO_x increase by after injection is solved by combination of after injection and EGR, and the trade-off curve regarding smoke, fuel consumption and NO_x is really improved.

The pioneering clarification of the multiple-injection effects and mechanisms and also solutions to the problems described above enabled the adequate use of multiple injections.

3. 3 Combustion System to Realize Both Increase in Power Density and Severely Low Exhaust Emissions

Since 2000’s, exhaust-emissions regulations have been becoming greatly stringent step by step. In the case of diesel engines, smoke level at medium and low loads should be first reduced for decreasing exhaust emissions in frequently used operating region. For this purpose, decrease in nozzle-orifice diameter of injectors is most effective and essential, so that injectors with the decreased nozzle-orifice diameter and increased number of nozzle orifices were widely adopted, leading to remarkably reduced smoke and then NO_x through increased EGR rate. However, maximum power, that is, maximum torque at high speed was notably reduced. The analysis results of our studies⁽⁸⁻¹⁰⁾ responding to this problem are as follows.

3. 3. 1 Shallow-dish-type Combustion Chamber

In conclusion, the solution to the above-mentioned problem was a shift in combustion chamber shape from a conventional deep-bowl type to a shallow-dish type. The cause and the related findings are the followings.⁽⁸⁻¹⁰⁾

(1) In a conventional combustion system with the deep-bowl cavity and a large-orifice-diameter nozzle, intense air-flow momentum generated by the cavity balances

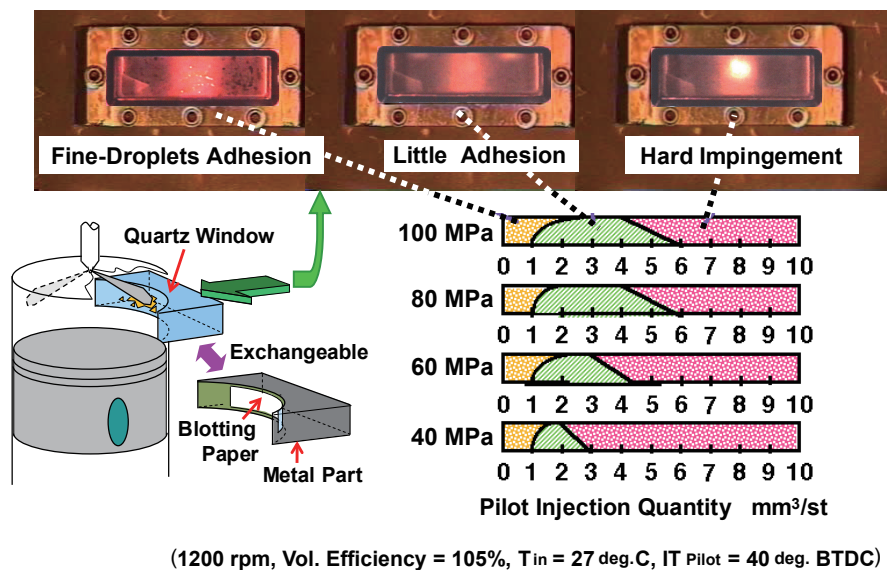


Fig. 4 Effect of injection quantity and pressure on fuel adhesion to cylinder wall.

with strong spray momentum by the large-orifice nozzle, leading to good fuel-air mixture distribution in the whole combustion chamber at high-speed and high-load conditions (the left-column case of Fig. 5). On the other hand, in the case of a small-orifice nozzle combined with the deep-bowl cavity, only spray momentum becomes smaller and thus most mixture is conveyed out of the cavity by the intense reverse-squish flow, as shown in the middle-column case of Fig. 5. Therefore, air in the cavity is not utilized, leading to high smoke level (i.e. lowered maximum power).

(2) By combination of the small-orifice nozzle and the shallow-dish cavity, air flow momentum is also suppressed and thus good momentum balance of air flow and spray is realized again, resulting in good mixture distribution (the right-column case in Fig. 5). With regard to emissions at part loads (i.e. low speed), flexibly increased injection pressure with CR FIE compensates insufficient mixing effect of the shallow-dish cavity due to the excessively weak air flow at low speed conditions.

(3) The factor governing “smoke-limited equivalence ratio” which determines maximum power was found to be a ratio of V_s/V_{sp} , where V_s is representative squish speed and analytically obtained with cavity diameter and engine speed, and V_{sp} is representative spray

speed and calculated with nozzle-orifice diameter and injection pressure.⁽⁹⁾ The smoke-limited equivalence ratio becomes a function of V_s/V_{sp} independently of engine size and FIE type, and thus specifications of the piston cavity and injection system to realize required maximum power can be determined.

(4) In reality, a high value of smoke-limited equivalence ratio, 0.88 was attained even at 4,000 rpm by keeping the V_s/V_{sp} value of 0.7 which is realized with very high injection pressure of 240 MPa generated by a prototype, amplified-pressure CR FIE,⁽¹⁰⁾ as shown in Fig. 6. This result predicted the possibility of nowadays high power-density level of 90 kW/L or more.

These pioneering results and findings clearly indicated the development direction of modern HSDI diesel combustion systems.

3.3.2 Combination of High Boost Pressure, High EGR Rate and High Injection Pressure

As described in Section 2.5.1, with increasing all of charging efficiency, EGR rate and fuel injection pressure, NO_x-Soot tradeoff is remarkably improved at medium and high load conditions. This technique was first proposed by New ACE for heavy-duty diesel engines.⁽¹¹⁾ Responding to the result of New ACE, it was evaluated in this study whether or not the technique

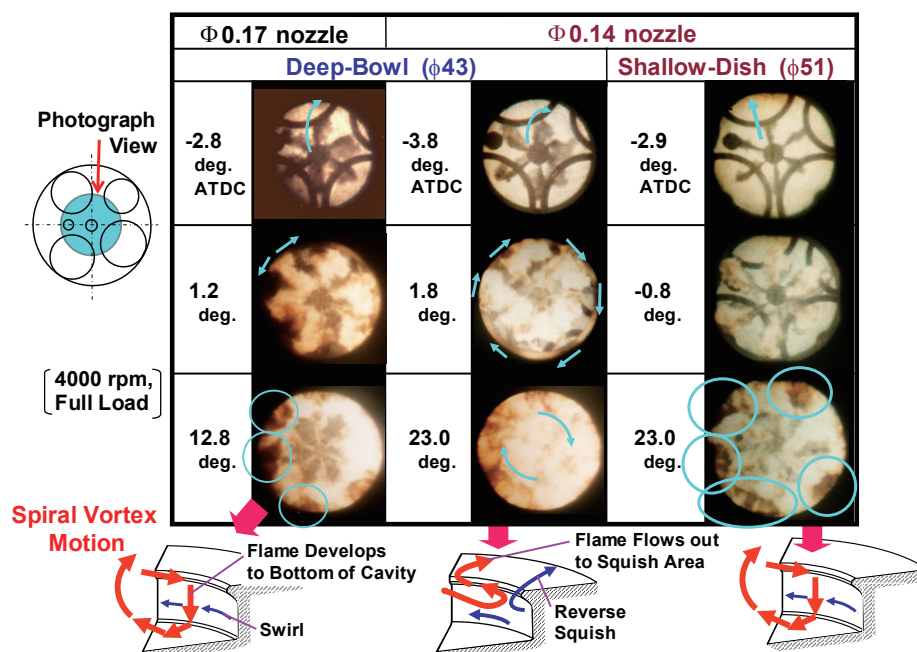


Fig. 5 Effect of nozzle orifice diameter and cavity shape on formation of spiral vortex motion for promoting fuel-air mixture distribution.

was really effective also for HSDI diesel engines.⁽¹²⁾
 (1) As shown in Fig. 7, the “high-boost-pressure (i.e. high charging efficiency) & high-EGR-rate” combustion system with high pressure injection drastically improved NOx-Soot tradeoff also for a HSDI diesel engine.

(2) As shown in Fig. 8, the analysis results of heat release rate, shadowgraph photograph and flame temperature distribution indicate that, by shifting in combustion system from conventional type to the “high-boost-pressure & high-EGR-rate” type, less luminous flame is generated, that is, formed soot amount is reduced, and combustion period becomes shorter. In addition, flame temperature is lowered in the whole flame region, more quantitatively describing, lowered by 260 K in the largest flame area, which reduces NOx by 84% in this case.⁽¹²⁾

(3) In conclusion, by the shift, oxygen volume fraction decreases from 18.5% to 15.8% in this case due to the increased EGR rate, whereas oxygen quantity increases by 1.46 times due to the increased charging efficiency.⁽¹²⁾ The former leads to lowered flame temperature and then notably low NOx, and the latter reduces soot (i.e. smoke). Higher injection pressure required in the “high-boost-pressure & high-EGR-rate” system is essential to keep sufficient spray-tip penetration against the increased in-cylinder gas density.

This study first clarified the cause of the emissions reduction and the required conditions on the “high-boost-pressure & high-EGR-rate” combustion method. This method is widely applied to

nowadays newly-developed diesel engines.

4. Our Researches of Alternative Combustion Systems

4.1 Dual-fuel Stratified PCCI Combustion

As an alternative combustion system, premixed-charge compression ignition (PCCI) combustion systems have been being developed since around 1995, because

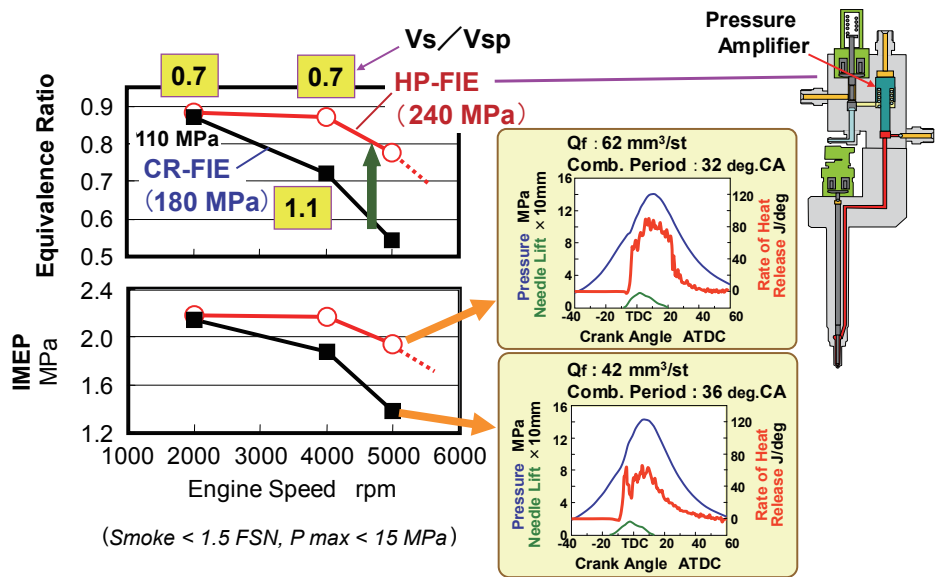


Fig. 6 Increase in smoke-limited equivalence ratio (i.e. IMEP) with extremely high injection pressure.

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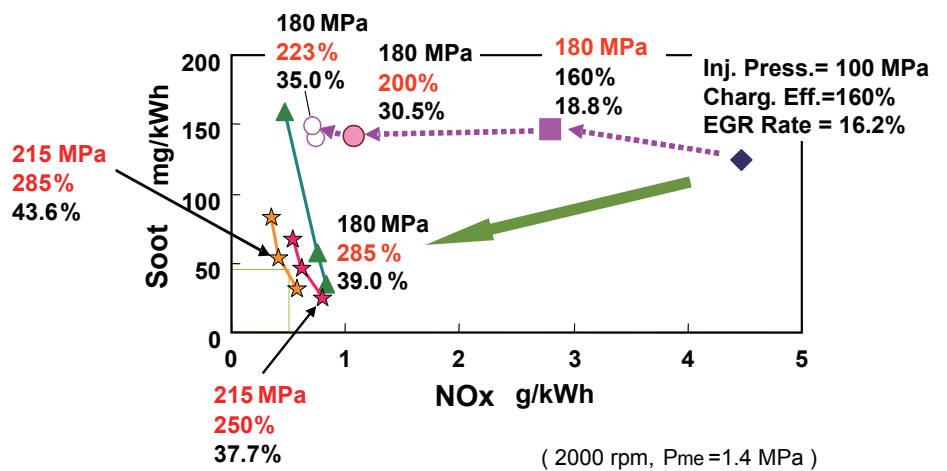


Fig. 7 Emissions reduction potential of “high-boost-pressure & high-EGR-rate” combustion system.

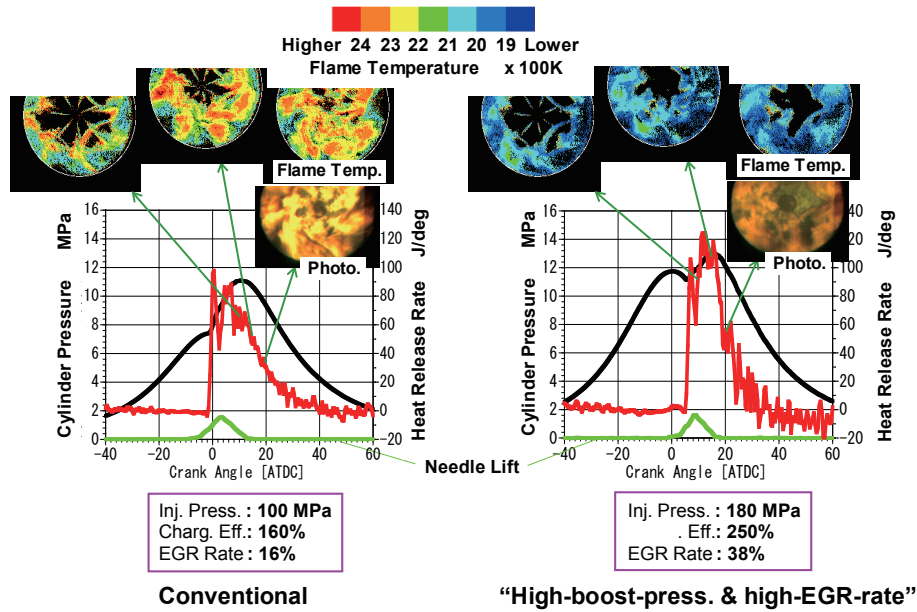


Fig. 8 Comparison of heat release rate and flame temperature distribution between conventional and “high-boost-press. & high-EGR-rate” combustion systems.

the PCCI combustion has the potential for reducing both NO_x and smoke to near-zero levels without any after-treatment systems and also for increasing thermal efficiency. However, the PCCI combustion has problems of misfire at low loads and premature ignition and excessive burning rate at high loads, which causes deteriorated thermal efficiency and severely increased noise, limiting the operating region. The ignition timing and burning rate, governed by temperature, heat capacity and oxygen concentration of the in-cylinder gas, are therefore controlled by EGR, supercharging, variable valve timing (VVT) and so on. But, unfortunately, PCCI combustion is very sensitive to the governing factors, and also those controlling factors of EGR and so on have a long response time. Therefore, control at transient operation is difficult, which still prevents the PCCI combustion from putting to practical use.

Responding to the problem, related researches were conducted and a solution was proposed⁽¹³⁾ as follows: (1) “Dual-fuel stratified PCCI” combustion, in which two fuels with opposite ignitability are used and both the concentration and ignitability of fuel vapor are stratified as shown in **Fig. 9**, is able to realize moderate combustion rate under keeping very low NO_x level without EGR, leading to moderate noise level, as shown in **Fig. 10**. As understood from a system setup shown in Fig. 10, the “dual-fuel stratified PCCI” have basically good controllability even at transient

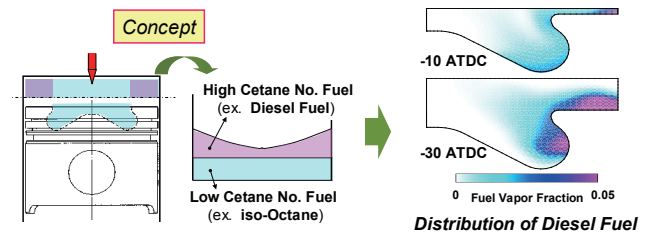


Fig. 9 Concept of fuel-air mixture distribution in “dual-fuel stratified PCCI” combustion and a practical example of diesel fuel distribution.

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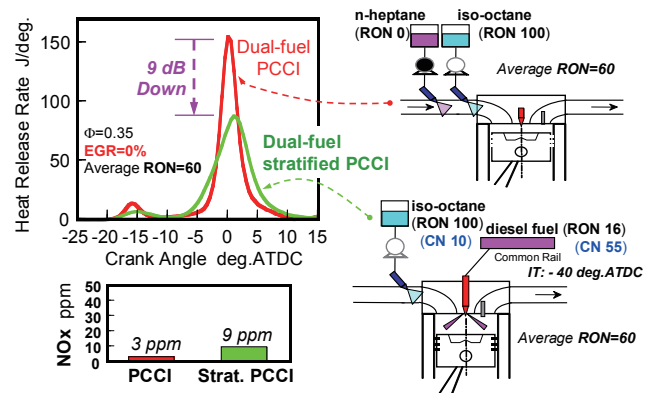


Fig. 10 Effect of stratification in fuel-vapor concentration and ignitability on burning rate and exhaust NO_x emission.

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operation.

(2) CFD analyses reveal the followings. In the case of ordinary PCCI combustion, ignition simultaneously occurs anywhere in the cylinder, leading to peaky combustion rate. On the other hand, in the case of the “dual-fuel stratified PCCI”, ignition starts in the outer region and then combustion zone gradually spreads into the inner region, leading to moderate combustion rate.⁽¹³⁾

The pioneering solution described above is still a rare method to put PCCI combustion to practical use. Regrettably, this concept has not yet been applied to passenger cars due to the necessity of two fuels, but is thought to be really useful for heavy-duty vehicles and has been succeeded to nowadays “RCCI” research works.⁽¹⁴⁾

NOx level of stringent Tier2-Bin5 regulation without any de-NOx catalysts mainly due to enlarged PCCI combustion zone, and simultaneously reduces fuel consumption due to the decreased heat loss by the

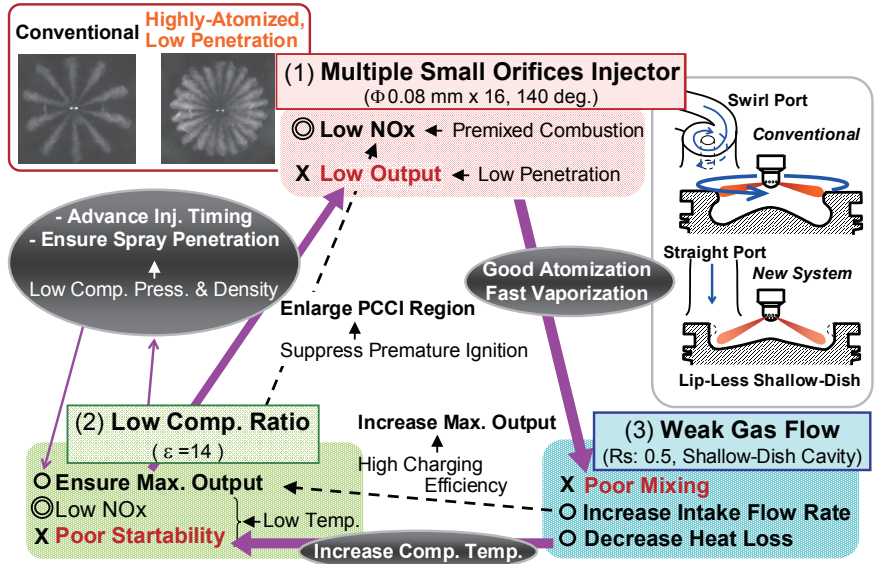


Fig. 11 Cause enabling “quiescent combustion system” of high efficiency and low emissions.

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4.2 Quiescent Combustion System with Multiple Highly-atomized Fuel Sprays

As decreasing exhaust emissions, fuel economy of diesel engines had been deteriorated due to injection timing retard, increase in EGR rate and so on. Therefore, a new combustion concept with both high thermal efficiency and low exhaust emissions was desired. Responding to this request, an ingenious, new combustion concept described below was created in this study.⁽¹⁵⁾

(1) “Quiescent combustion system” described in Fig. 11 consisting of multiple highly-atomized sprays by a multiple small-orifices injector, weak in-cylinder gas flow by both a low-swirl-ratio intake port and a lip-less shallow-dish cavity, and low compression ratio, effectively decreases heat loss and NOx under keeping the maximum output, as shown in Fig. 12. The “quiescent” system has the potential to clear the

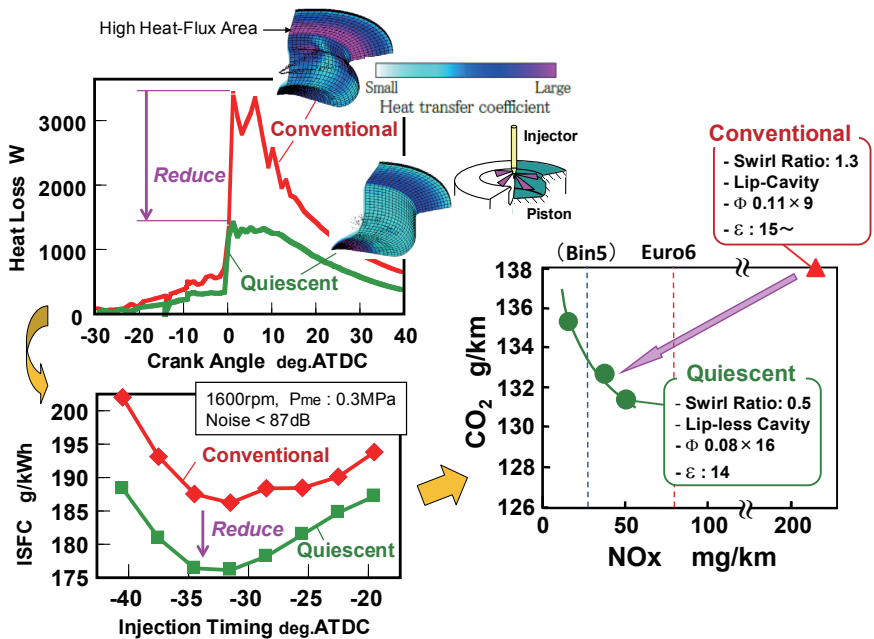


Fig. 12 Improvement of efficiency-emissions trade-off by “quiescent combustion system”.

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suppressed gas flow.

(2) In generality, each factor of the extremely-small-orifices injector, weak gas flow and low compression ratio leads to each problem of poor fuel vapor distribution due to the insufficient spray-tip penetration, poor fuel-air mixing and poor cold-start characteristic, respectively. Thus, it had been quite difficult to apply these factors to a real engine. However, it was found in this study that these problems are able to be overcome by combining all of these factors as shown in Fig. 11. As indicated in this figure, lowered compressed-gas density around compression TDC due to the low compression ratio enhances spray-tip penetration, good atomization and fast vaporization of injected fuel due to the extremely-small-orifices injector ensures sufficient fuel-air mixing, and the decreased heat loss due to the weakened gas flow gives necessary cold-start ability.

The findings in this study are epoch-making and are being utilized mainly for next-generation, popular-edition diesel engines described in Section 2.5.2.

5. Development of Analytical Tools

As mentioned above, various kinds of analytical methods and tools including special apparatuses were developed in the studies of ours. Among them, as one of the most important tools, a universal diesel engine simulator called “UniDES”⁽¹⁶⁾ is introduced here. This simulator is very useful to plan a new engine system and roughly determine main specifications of the combustion system. Additionally, it is very helpful to adjust control parameters on injection and combustion systems. Features of the “UniDES” are as follows:

(1) The core of “UniDES” is a “multi-zone PDF model”, in which zones corresponding to spray regions and ambient gas region are introduced and each spray zone is further divided into premixed and diffusion combustion zones. In-cylinder gas flow such as swirl and squish are

calculated based on Arai’s model,⁽¹⁷⁾ and distributions of various fuel concentrations in the combustion zones are represented with a probability density function (PDF). With regard to combustion reaction rates, the chemical reactions before and after ignition in the mixture zones are represented with the “shell model”⁽¹⁸⁾ and the “LTCTC model”,⁽¹⁹⁾ respectively. As shown in Fig. 13, the “multi-zone PDF model” gives very good agreements between simulation results and experimental data. This model can also represent PCCI combustion and thus analyze switching behaviors between ordinary diesel and PCCI combustions.

(2) The “UniDES” gives various kinds of information on in-cylinder phenomena such as spray zones behavior, history of equivalence ratio and temperature of each gas package, history of nitrogen oxide (NO) concentration of each zone, and so on.⁽²⁰⁾ Some of them are shown in Fig. 14. The information of spray zones behavior enables to judge whether or not the smoke-forming interference between pilot- and main-injection fuels described in section 3.2 occurs, and then to roughly determine optimum pilot-injection timing. The histories of both the equivalence ratio and temperature of each gas package and NO concentration of each zone indicates what gas zone is a source of

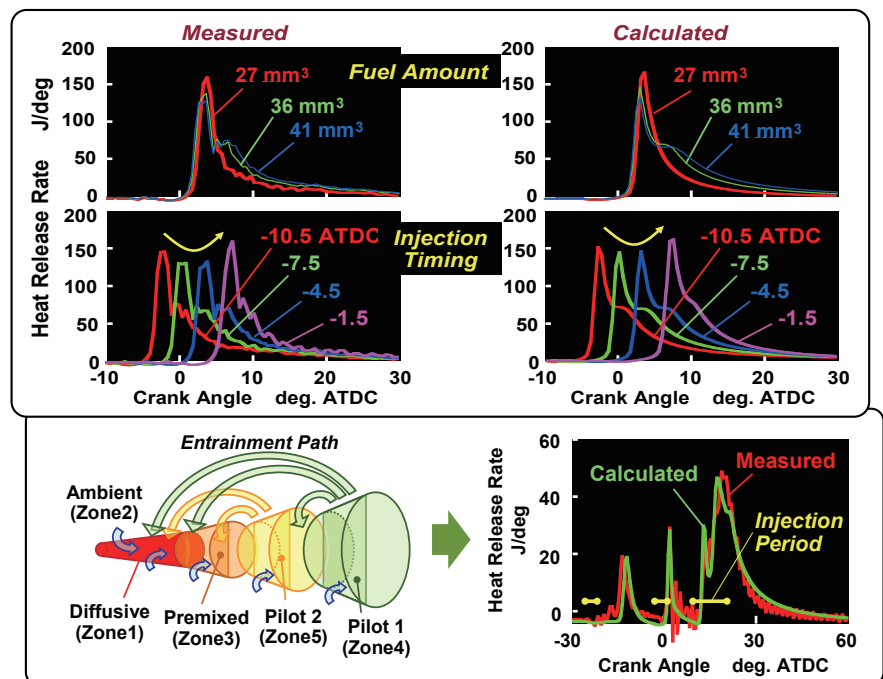


Fig. 13 Potential of “multi-zone PDF model”: comparison in heat release rate between measured and calculated results.

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exhaust emissions, leading to an exact countermeasure. (3) The “UniDES”, an in-house turbocharger model⁽²¹⁾ and a combustion noise simulator⁽²²⁾ were all linked to a commercial code “GT-Power”, leading to a diesel engine system simulator. As shown in an evaluation example of transient behavior during acceleration in EC mode of Fig. 15, the simulator is able to give good agreements between calculated and measured data.⁽²³⁾

The “UniDES” and the diesel engine system simulator are both actively being applied to planning new engines and also adjusting the engine control parameters, resulting in effectively saving development time and labor.

6. Prospect of Future Researches

In the near future, it is thought that increases in power and torque densities are continued for further engine downsizing, and simultaneously innovative increase in thermal efficiency of diesel engines is required under realizing ultra-low exhaust emissions.

From the view point of developing diesel combustion systems, the former trend requires exact understanding of in-cylinder phenomena especially under high-load and high-speed conditions, and thus analysis methods and tools applicable to high pressure (i.e. high density) and high temperature conditions are necessary. Responding to this, a next-generation, optically accessible single-cylinder engine which sustains high cylinder pressure of 20 MPa and high-speed operation of 6,000 rpm has been developed in our laboratories.⁽²⁴⁾ By using both this engine and more sophisticated analysis methods, in-situ analyses should be conducted.

With regard to the latter requirement, thorough reduction of various losses is most important. Among the losses, heat loss from high-temperature working gas to walls of combustion chamber and exhaust paths should be first reduced. Responding to this issue, an innovative heat-insulation method named “Temperature swing” has been created.⁽²⁵⁾ With this method, harmful influence such as worsened exhaust emissions and lowered thermal efficiency of conventional heat-insulation methods is able to be eliminated. Hereafter, putting the

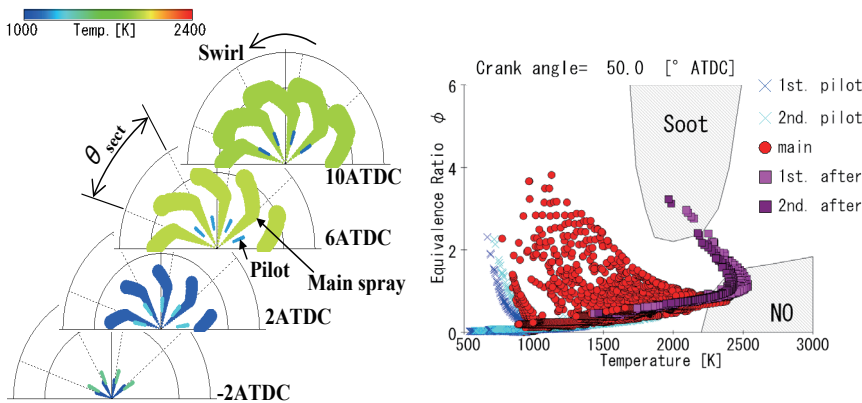


Fig. 14 Example of information on in-cylinder phenomena given by “UniDES”: spray zones behavior and gas state plots on ϕ -T map.

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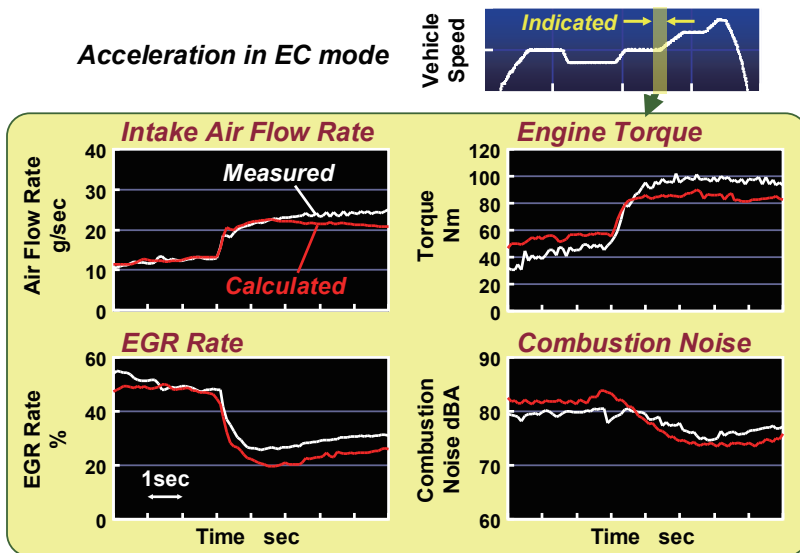


Fig. 15 Potential of diesel engine system simulator with “UniDES”: comparison in acceleration behavior of an engine system between measured and calculated results.

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“Temperature swing” method into practical use should be speedily accomplished and simultaneously a new combustion concept suitable for this method is desired to be clarified. In addition, research and development of thermal management including control of heat flux to the walls and effective heat-recovery techniques are also important.

Also hereafter, our laboratories will play key roles on the above-mentioned researches for realizing a next-generation diesel engine with both sufficiently high power density and innovatively high thermal efficiency.

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