Review

Research and Development Trends in Combustion and Aftertreatment Systems for Next-Generation HSDI Diesel Engines

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次世代HSDIディーゼルエンジン用の燃焼・後処理システムに関する研究・開発動向

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Abstract

Recently, the performance and exhaust emissions of high-speed direct injection (HSDI) diesel engines for passenger cars have been rapidly improved. In these engines, the power and torque densities have reached 50-60 kW/l and 160-170 Nm/l, respectively. In addition, the noise, vibration and harshness (NVH) and exhaust emissions have been decreasing toward a level that is comparable to that of gasoline engines. Furthermore, the maximum brake thermal efficiency has reached 42-43% and both city and highway fuel economy is excellent. Therefore, the percentage of diesel passenger cars in Europe has been increasing remarkably and is forecasted to reach 48% in 2007.

The developments of common-rail (CR) injection systems, high-efficiency aftertreatment devices such as the diesel particulate filter (DPF) and catalysts, and advanced electronic control systems are listed as major technical backgrounds of the progress in HSDI diesel engines. In the present review, recent trends in research and development of the above-listed component technologies, primarily regarding combustion and aftertreatment systems, are outlined. Finally, critical technical areas that must be addressed in order to realize an ultra-clean and high-performance diesel engine are presented.

Keywords Diesel engine, Fuel injection, Combustion, Exhaust aftertreatment, Fuel, Control

要　旨

近年，乗用車用HSDI (高速・直噴) ディーゼルエンジンは長足の進歩を遂げており，性能面では比出力が50-60kW/l，比トルクは160-170Nm/lに及びスポーツ走行にも対応しうるうえ，振動・騒音や排気もガソリン車と同等レベルに近づきつつある。さらにディーゼルエンジンは，乗用車用の小型においても最高熱効率が42-43%と現有原動機中最高の効率を有し，市街地から高速走行までの全域で燃費が良い。このため，欧州でのディーゼル乗用車のシェアは増加し続けており，2007年には48%に達するとする予測がある。この技術的背景としては，コモンレール噴射システムの出現とこれを活用する燃焼法の開発，DPF (ディーゼルパティキュレートフィルタ）や各種触媒の開発，ならびに制御技術の進展などがある。本稿では，燃料噴射・燃焼系および排気後処理系を中心に，上記の鍵となった各要素技術における近年の研究・開発動向と現時点での課題を概観する。そのうえで，超低排気で高性能なディーゼルエンジンを実現するうえで重要になる技術項目と，その実現の可能性を展望する。

キーワード ディーゼルエンジン，燃料噴射，燃焼，排気後処理，燃料，制御

1. Introduction

As the number of cars continues to increase steadily, both the health effects of exhaust emissions and the greenhouse effect of CO_2 emissions have become increasingly disturbing. Therefore, fuel cells have become increasingly appealing as a new power source for cars due to their potential clean emissions and high thermal efficiency. However, fuel cells still have many problems which must be solved before practical application is possible, and so gasoline and diesel engines will likely continue to be the chief power source of automotive power for several decades.

Diesel engines have a serious drawback that the amount of exhaust particulate matter (PM) is comparatively larger than that of gasoline engines. A solution to this problem is urgently needed. On the other hand, diesel engines have the highest potential to prevent the greenhouse effect due to their highest thermal efficiency among the power sources for automobiles. Diesel engines provide the best fuel economy and high torque at medium and low engine speeds and therefore are widely used in trucks and buses worldwide. However, the number of diesel-powered passenger cars is limited due to both the black smoke, which is composed primarily of soot and is a major component of PM, and the large noise, vibration and harshness (NVH).

Recently, however, the performance and emissions of diesel engines for passenger cars have both been improved rapidly, due primarily to the appearance of common-rail (CR) injection systems, high-efficiency aftertreatment systems and more advanced electronic control systems. Currently, passenger-car diesel engines have high power density (50-60 kW/l) and high torque density (160-170 Nm/l), which are sufficient for sporty driving conditions. In addition, the NVH levels of the current diesel-powered cars have decreased to levels comparable with those of gasoline-powered cars, and exhaust emissions have also been reduced drastically. Furthermore, the maximum brake thermal efficiency of these diesel engines has reached 42-43%, and fuel economy under actual driving conditions is excellent in both city and highway modes. Therefore, the percentage of diesel passenger cars in Europe has been increasing remarkably and is projected to reach 48% in 2007.

Hereinafter, recent trends in research and development of the component technologies for passenger-car high-speed direct injection (HSDI) diesel engines, primarily regarding combustion and aftertreatment systems, are outlined. In addition, important technical problems involved in the realization of an ultra-clean and high-performance diesel engine are discussed.

2. Fuel injection system

2. 1 Jerk-type injection system

The conventional fuel injection system is typically a pump-pipe-nozzle system, a jerk-type injection system in which fuel is injected only when a plunger compresses the fuel in the plunger barrel. Since high injection pressure is very effective in reducing exhaust smoke, the nozzle-side maximum injection pressure of the jerk-type injection system has been raised to 160 MPa.

Another jerk-type injection system is the unit injector (UI), in which the pump and nozzle are combined. The UI does not have a high-pressure pipe so that higher peak injection pressure is realized. Recently an electronic-control UI having a peak pressure of 205 MPa has been developed, thus contributing to a remarkable increase in power density.[1)]

However, in the jerk-type injection system, the injection pressure depends on engine speed and load (injection quantity) and fuel can be injected only near compression TDC. Thus, in this system, injection pressure cannot be adjusted up to the desirable level for PM reduction, especially at low-speed conditions. In addition, as discussed in the following section, multiple injections cannot be realized in this system.

2. 2 Common-rail injection system

The CR injection system is a fully electronically-controlled, high-pressure fuel injection system, which has the potential to solve the above-mentioned problems associated with jerk-type systems. A schematic diagram of a CR system[2)] is shown in **Fig. 1**. High-pressure fuel is continuously supplied into the common-rail, which is an accumulator that is common to all cylinders, and the pressure is adjusted to the optimum level depending on the engine operating conditions. In addition, multiple injections, 5-7 injections per cycle, for which the timing and fuel quantities are completely variable, are possible. These two functions, flexible adjustment of the injection pressure and multiple injections, remarkably improve engine performance and reduce both emissions and NVH. Thus, clarifying the optimum injection pattern in complex multiple injections is important, as described in detail in the following research report of this special issue.

Initially, the CR system had a problem that the maximum injection pressure could not be increased up to the highest level realized in the jerk-type system, because the CR system always maintains the fuel at high pressure. However, the CR system has been steadily improved so that the maximum injection pressure, which was 135 MPa in the first-generation systems, has been raised to 160-180 MPa in recent second-generation systems.

3. Combustion system

3. 1 Ordinary diesel combustion

In the case of ordinary diesel combustion, the entire process from fuel injection to combustion should be completed in a very short time, ranging from 2 to 3 ms. This feature is the cause of the high levels of exhaust PM, but is simultaneously the source of the high thermal efficiency. Recently, the tendency has been to increase smoke because the exhaust gas recirculation (EGR) rate has increased, which has in turn decreased nitrogen oxide (NOx) emission.

A decreased nozzle-orifice diameter is a very effective means of reducing smoke. However, decreased nozzle-orifice diameter causes the momentum of the fuel spray to decrease so that the spray speed becomes relatively lower than the in-cylinder gas speed. This imbalance between the spray and gas speeds causes the smoke level to increase, especially under high-speed and high-load conditions, because further increasing the injection pressure is impossible under these conditions, even in CR systems, which leads to a decrease in maximum output. This problem has been solved by improving the combustion chamber configuration, which is also described in the following research report.

The swirl flow generated by specially shaped intake ports is also important. Optimizing the swirl speed depending on the engine operating conditions is an effective means by which to not only reduce emissions but also increase thermal efficiency. Thus, recently, variable-swirl intake ports have been used frequently and are currently being developed further.

3. 2 New/Alternative combustion

3. 2. 1 Premixed-charge compression ignition

Research on premixed-charge compression

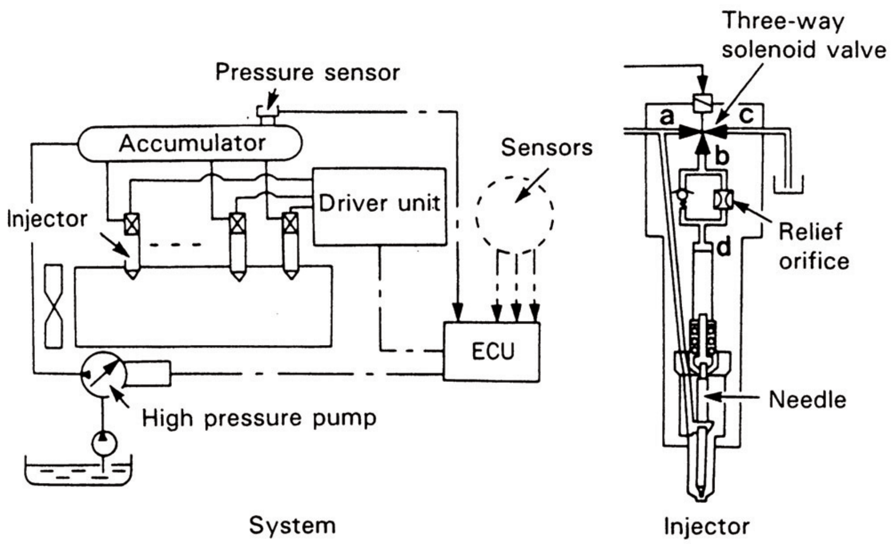

Fig. 1 Common-rail fuel injection system.[2)]

ignition (PCCI) combustion, in contrast to ordinary diesel combustion which is based on diffusion combustion, has been progressing since around 1995.[3)] In PCCI combustion, fuel is injected into the intake port or cylinder at variable timing during intake and/or the middle stage of the compression stroke and is then sufficiently mixed with surrounding air for a longer time before auto ignition, leading to premixed combustion. This concept is attractive due to the potential for not only reducing NOx and smoke emissions to nearly zero levels, but also further increasing thermal efficiency.

However, the PCCI combustion has the problems of misfire at low load near idling and of premature ignition and excessive burn rate at high load, which causes the deterioration of thermal efficiency and severely increases noise, leading to a limited operating region under low and medium loads. The ignition timing and burn rate are governed by the temperature and heat capacity of in-cylinder gas as well as oxygen concentration. Thus, the controlling factors for ignition timing and burn rate include EGR, supercharging, and variable valve timing (VVT). Unfortunately, PCCI combustion is so sensitive to these controlling factors that the robustness is very low. In addition, the controlling factors of EGR and supercharging have such a lengthy response time that control at transient operation is difficult. Therefore, the development of new controlling factors having fast response and sophisticated control methods are desired.

Furthermore, an injector having weak spray-tip penetration and high diffusiveness is required for PCCI combustion in order to prevent fuel adhesion to the cylinder wall and soot formation. In contrast, an injector having the completely opposite characteristics is required for ordinary combustion. Thus, a new injection system having variable spray characteristics is necessary in order to simultaneously respond to these different requirements because both combustion modes should be combined to ensure operation over the entire operating region. Although the numerous difficult problems which must be solved in order to put PCCI combustion to practical use exist as mentioned above, active research is still continued due to the potentially large impact of the successful application of PCCI combustion.

3. 2. 2 Low-temperature combustion

Low-temperature combustion (LTC) has also been developed.[4)] This concept is based on the finding that both NOx and smoke become nearly zero under quiet combustion, even under stoichiometric and rich conditions, despite the limited operating region at low loads, when EGR rate exceeds a critical value, because the gas temperatures in combustion zones become too low to form NOx and soot.

Since, for the ordinary combustion system, the LTC can be realized only by carefully setting the EGR rate and injection timing, no serious problem is encountered in putting the LTC to practical use, in contrast to the case of PCCI combustion. Furthermore, the ability to realize slightly lean and rich diesel combustion without NOx and smoke emissions is very useful in not only activating oxidation catalysts by supplying HC and CO, but also generating "rich spike" which is an intermittent rich-exhaust-gas flow introduced to NOx storage-reduction (NSR) catalysts. The only problem associated with LTC is the need for more sophisticated control in order to allow smooth switching between the LTC and the ordinary combustion modes due to the discontinuity in the EGR rate and the injection timing required for both combustion modes.

4. Aftertreatment system

The major harmful substances in diesel exhaust gas are PM, NOx, CO and HC. Generally, CO and HC can be purified by diesel oxidation catalyst (DOC), and therefore technologies to purify PM and NOx are urgently required.

4. 1 PM purification system

DOC and the diesel particulate filter (DPF) are both effective means to purify PM. The PM oxidation rate of DOC is fairly low, whereas the DPF can effectively purify PM, including ultrafine particles, at very high rates of over 80% of mass and of over 97% of particles. Thus, at present, research and development is concentrated on the DPF.

The DPF consists of a ceramic filter having very small pores. The PM accumulated in the DPF is forcedly oxidized to regenerate the DPF, because diesel exhaust-gas temperatures in city driving modes are lower than the soot thermal oxidation temperature of approximately 600ºC. In the DPF, both adequate judging of the regeneration timing and the means of forced PM oxidation are important. If the regeneration timing is inadequate, the DPF can be partially melted by excessive heat generated in forced PM oxidation. Thus, both accurate detection of the amount of accumulated PM and the control method of the DPF temperature are essential. Previously, burners and electric heaters were used for forced PM oxidation; however, deterioration of fuel economy and difficulty in uniform regeneration were major problems. Recently, a DPF system having fuel-borne catalyst (FBC), as shown in **Fig. 2**, has been developed and applied to a passenger car.[5] In this system, the soot thermal oxidation temperature is reduced to approximately 400ºC by FBC (cerium), and the exhaust-gas temperature is increased to approximately 450°C by the combination of post injection and DOC located upstream of the DPF. The problems associated with this system are both the need to replenish the FBC and the need to clean the DPF so as to remove accumulated ash.

Another DPF system is a continuously regenerating DPF system, which consists of a DOC and a DPF. The accumulated PM is continuously oxidized by NO_2 which is generated by oxidizing NO in the upstream DOC. The problems of this system are both the need of an accurate control to maintain the mass ratio of NO/PM in engine-out exhaust gas over a critical value and the need of a high purification-rate NOx catalyst with which to sweep NOx out of the DPF.

4. 2 NOx purification system

4. 2. 1 SCR catalyst

Selective catalytic reduction (SCR) catalysts have a clear advantage that these catalysts are not poisoned by sulfur contained in the fuel or the lubricant. These catalysts are classified into two types: the HC-SCR system, in which the reductant of NOx is HC, and the Urea-SCR system, in which the reducing agent is ammonia generated from urea. The Urea-SCR system has a high NOx purification rate but has been developed exclusively for heavy-duty trucks and buses due to deficiencies in the infrastructure with respect to urea supply.

For passenger cars, HC-SCR systems have been developed with the purposes of improving catalyst materials and control methods needed to maximize the NOx purification rate, as well as minimize the deterioration of fuel economy. The results are described in detail in the following three research reports. However, the NOx purification rate of the ordinary HC-SCR is low (approximately 30%), and even in plasma-assisted HC-SCR systems, the best NOx purification rate is only approximately 45%. Thus, recent works to develop NOx catalysts for passenger cars have been focused primarily on NSR type catalysts.

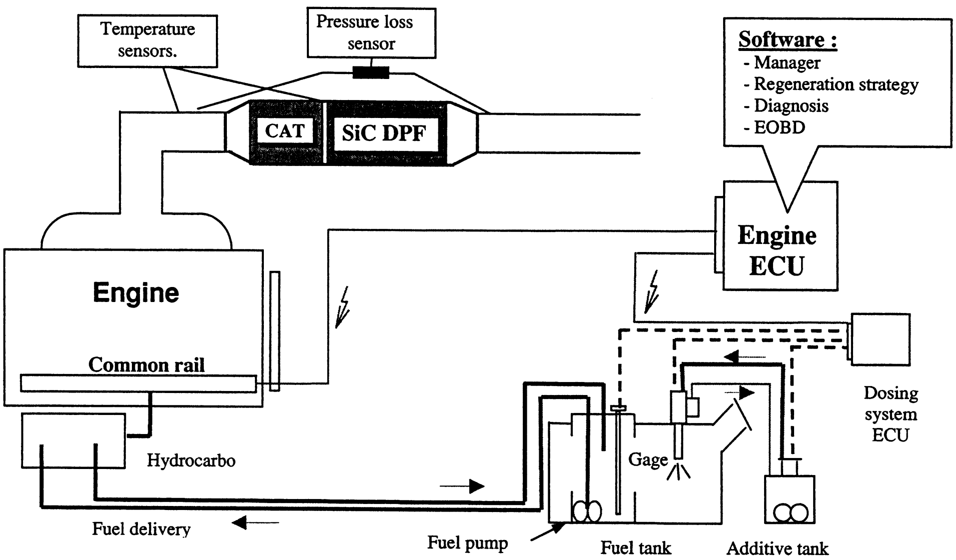

Fig. 2 DPF system with fuel-borne catalyst.[5]

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4. 2. 2 NSR catalyst

NSR catalysts have a high NOx purification rate of approximately 80% or more in fresh catalysts. The mechanism of NSR catalysts is that the exhaust NOx in lean conditions is stored on the catalyst surface, and the stored NOx is reduced in rich conditions when the exhaust gas does not contain any oxygen. Gasoline engines can easily realize rich combustion, and also, by using an oxidation catalyst located upstream of the NSR catalyst, gasoline engines can make the oxygen concentration zero and form a large amount of CO and H_2, which are very effective in NOx reduction. Therefore, NSR systems have already been applied to lean-burn and direct-injection gasoline engines.

In diesel engines, on the other hand, realizing rich combustion is rather difficult due to the dense smoke, and eliminating oxygen from the exhaust gas is also difficult even with rich spike, thus leading to a low NOx reduction rate. In addition, diesel exhaust-gas temperatures are fairly lower than those of gasoline engines, and are frequently out of the temperature window of NSR catalysts in which high NOx purification rates are realized. Furthermore, since diesel fuel contains a great deal of sulfur (500 ppm in Japan at present), ensuring the durability of NSR catalysts is still a very difficult task due to sulfur poisoning of the catalyst.

Recently however, rich spike with lower oxygen concentration, increased catalyst bed temperature and regeneration from sulfur poisoning have all been realized by, for example, smokeless-rich LTC and post injection with a CR system. Furthermore, the NSR catalyst material for diesel application has been steadily improved, and a clear trend has appeared whereby the sulfur content in fuel is reduced to 50 ppm in 2005 in Japan and Europe. Thus, the problems associated with NSR catalysts are steadily disappearing.

4. 3 Four-way catalyst

Recently, a four-way catalyst system known as the Diesel Particulate-NOx Reduction system (DPNR)[6] has been developed which has the potential to simultaneously purify the four harmful substances of PM, NOx, CO and HC.

DPNR is a DPF of which the surface is coated by a kind of NSR catalyst. In the DPNR system, PM is thought to be oxidized by active oxygen generated in both the NOx storage and reduction processes, together by excessive oxygen under lean conditions.[6] In order to maximize NOx purification and PM oxidation rates, precise control of both the degree and timing of rich spike and regeneration from sulfur poisoning is required. For this purpose, a sophisticated system (**Fig. 3**), consisting of both a CR engine having an exhaust-port injection (EPI) device and a DPNR catalytic converter, and a system control method (**Fig. 4**) associated with LTC, post injection and EPI have both been developed.[6]

Other four-way catalysts, such as combination systems of the DPF and NOx catalyst and the plasma-assisted catalyst system, are also being developed. In the plasma-assisted system, catalysts can be highly activated from low temperature; however, deterioration of fuel economy is a major problem.

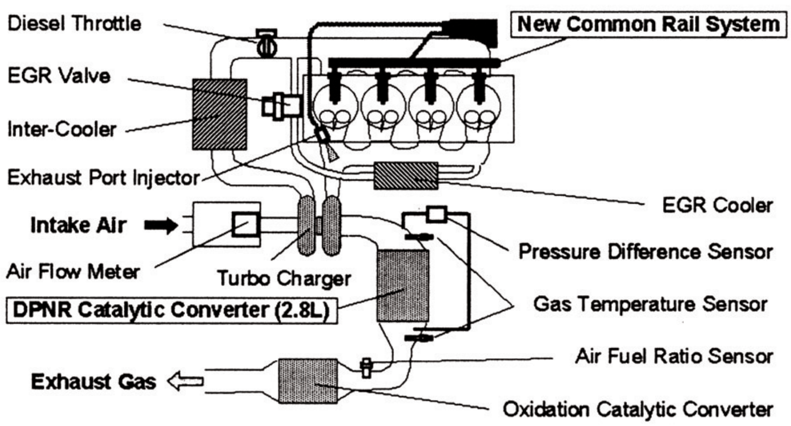

Fig. 3 DPNR System.[6]

5. Fuel

Improvement of fuel properties is very important to the reduction of PM and the prevention of catalyst deactivation.

Further reduction of sulfur content is desired in order to ensure the durability of NSR catalysts, which have a high NOx purification rate.

In order to meet future emission standards scheduled after 2005, the engine-out PM should be reduced at least by 30-50% compared with the best level in 2002, even with high-efficiency after-treatments. At present, it has been widely recognized that the content of aromatics, especially polycyclic aromatic hydrocarbons (PAH), should be decreased, and also high boiling-point components should be eliminated, in order to achieve PM reduction. On the other hand, recent studies have indicated that the molecular structure of paraffins in diesel fuel can have a large effect on PM formation. These findings are described in the following research report. Thus, the relation between fuel properties and the amount of exhaust PM requires further careful examination.

Recently, gas-to-liquid (GTL) fuel, which is generally a synthetic fuel obtained from natural gas, has attracted attention due to the possibility of freely controlling the components and distillation characteristics of this fuel. Thus, GTL fuel is considered to be very useful not only for PM reduction but also for new/alternative combustion methods due to the controllability of ignition and evaporation properties.

6. Control of combustion and aftertreatment systems

As described in **chapters 3** and **4**, high-response, precise control of combustion and aftertreatment systems has been essential to realizing a remarkably improved diesel engine system.

For the control of injection and combustion systems, a cylinder-pressure-based control is being developed. This is a kind of feed-back control method and enables precise controls of injection events, including multiple injections, and combustion control factors such as EGR rate and swirl level.

Another important area of research is a model-based control in which the control is executed based on predicting future states of the control subjects using simulation models. This method would enable high-response control, which is suitable even for transient behavior, and is expected to be very useful for the controls of PCCI combustion, aftertreatment systems and a total system comprising an engine and aftertreatment devices. The development of simple

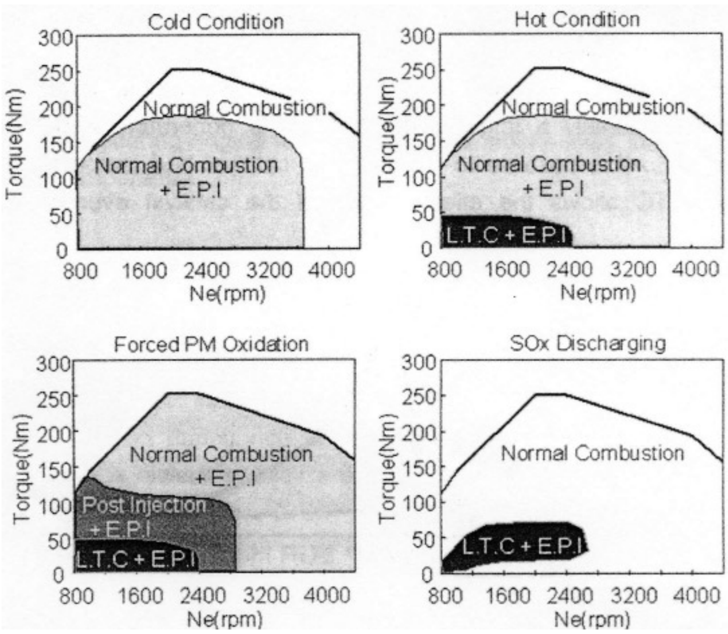

Fig. 4 DPNR system control for each condition.[6)]

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simulation models having high accuracy and increased potential with respect to engine control unit (ECU) are desired.

7. Prospect of an ultra-clean and high-performance diesel engine

Component technologies for the HSDI diesel engine have made remarkable progress during the last decade, not only in the areas described above, but also in the areas of turbo-charging and engine structural technologies. The last decade was spent mainly in the development of individual component technologies, and thus the results of several of these studies have not yet been incorporated into current mass-production engines. In addition, some diesel engine technologies require more time to achieve the final target level. Thus, the completion of these developments at the soonest possible time is important. Secondly, clarification of the best combination of combustion and aftertreatment systems depending on vehicle type, and the selection of optimal component technologies for the system in question are necessary. Finally, integration of these technologies through a sophisticated management system is also important. In the near future, an engine management technology achieved via a sophisticated control algorithm will become a key technology for HSDI diesel engines to progress further more into the next decade. An ultra-clean and high-performance diesel engine will appear when the above-mentioned development and integration of the technologies is accomplished.

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