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Ultra-Clean Combustion Technology Combining a Low-Temperature and Premixed Combustion Concept for Meeting Future Emission Standards

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Ultra-Clean Combustion Technology Combining a Low-Temperature and Premixed Combustion Concept for Meeting Future Emission Standards

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ABSTRACT

Experimental investigations were conducted with a direct-injection diesel engine to improve exhaust emission, especially nitrogen oxide (NOx) and particulate matter (PM), without increasing fuel consumption. As a result of this work, a new combustion concept, called Modulated Kinetics (MK) combustion, has been developed that reduces NOx and smoke simultaneously through low-temperature combustion and premixed combustion, respectively. The characteristics of a new combustion concept were investigated using a single cylinder DI diesel engine and combustion photographs. The low compression ratio, EGR cooling and high injection pressure was applied with a multi-cylinder test engine to accomplish premixed combustion at high load region. Combustion chamber specifications have been optimized to avoid the increase of cold-start HC emissions due to a low compression ratio. The results indicate the possibility of obtaining ultra-clean internal combustion engines capable of meeting Ultra Low Emission Vehicle (ULEV) regulations in the 21st century.

INTRODUCTION

Nitrogen oxide (NOx) and particulate matter (PM) emissions of diesel vehicles are regarded as a source of air pollution, and there is a global trend to enforce more stringent regulations on these exhaust gas constituents in the early years of the 21st century. On the other hand, the excellent thermal efficiency of diesel engines is certainly a welcome attribute from the standpoints of conserving energy and curbing global warming. In considering ways of reducing exhaust emissions further in the coming century, one approach to lowering NOx and PM levels is the direct-injection (DI) diesel engine, which is advantageous for curbing CO_2 emissions.

Figure 1 shows how much NOx emissions would have to be reduced for a conventional DI diesel that does not incorporate any emission reduction technologies in order to comply with current and future regulations for gasoline engines. NOx emissions would have to be reduced by 88% to meet the current standard for gasoline engines and by 96% to clear the more stringent standard set to be enforced in 2000. Moreover, a reduction of 98% would be required to reach the Ultra Low Emission Vehicle (ULEV) regulations of Tier2.

Against a backdrop of societal demands for cleaner vehicles, a great deal of research on new emission control technologies is being done today using DI diesel engines that provide high thermal efficiency. There has been a growing move in recent years to achieve radical improvements in emission performance by re-examining different forms of combustion, notably lean premixed combustion [1-6] like Homogeneous Charge Compression Ignition; HCCI. This HCCI combustion has been the focus of much interest for significant reducing NOx and soot. HCCI with the early injection can reduce NOx emissions by 90-98% in comparison to conventional Diesel combustion. However, HC and CO emissions are high level and fuel consumption deteriorates [6]. In HCCI combustion technology, a formation of homogeneous condition avoiding fuel-wall interaction is the biggest subject for achieving high thermal efficiency, reducing HC emission and avoiding oil dilution. Furthermore, the injection timing significantly influences exhaust emissions and fuel consumption. The main challenges of this combustion are controlling the onset of combustion [7].

The authors have used a high-efficiency DI diesel engine to originate a new combustion concept called Modulated Kinetics, which simultaneously reduces NOx and smoke levels by reconciling low-temperature combustion with premixed combustion[8-10]. The first generation of the MK concept was applied to develop a new type of DI diesel engine. At present, research is under way on the second generation of MK combustion aimed at expanding the region where this combustion concept is used in order to improve emission performance further.

This paper describes the emission characteristics of the second generation MK combustion concept that applied the prolonging ignition delay and the shortening injection duration. The combustion chamber specification was optimized to reduce the HC emissions under the cold condition. The results indicate the possibility of obtaining ultra-clean internal combustion engines for the Ultra Low Emission Vehicle (ULEV) regulation of California at the 21st century.

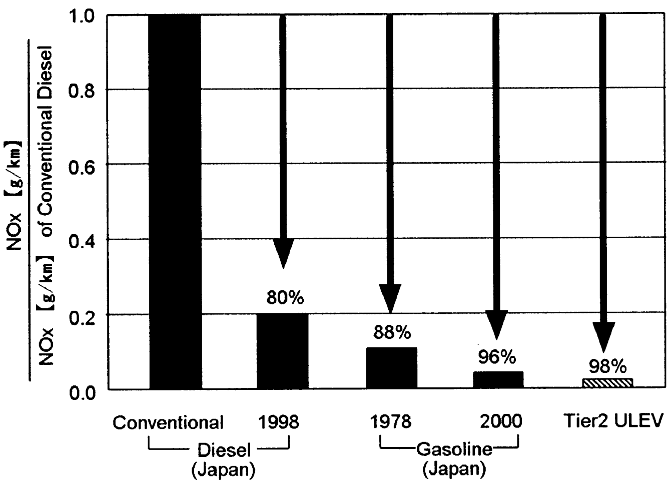


Figure 1. NOx Reduction Rate Requirements of Regulations

BASIC CONCEPT OF MK COMBUSTION

The MK concept can be essentially characterized as a low-temperature, premixed combustion system that is aimed at simultaneously reducing NOx and PM emissions, which is a major issue for DI diesel engines. The basic concept of MK combustion is explained schematically in Fig. 2.

Because NOx formation is strongly dependent on the combustion temperature, one effective way to reduce NOx emissions is to lower the combustion temperature. Low-temperature combustion is accomplished in the MK combustion concept by applying heavy exhaust gas recirculation (EGR) to reduce the oxygen concentration. Usually, reducing the oxygen concentration, however, results in a higher smoke level. Since it was concluded that a higher smoke level would be unavoidable with diffusion combustion, an investigation was made of a premixed combustion process, marking a departure from the methodology pursued previously. An attempt was made to reduce NOx and smoke emissions simultaneously through the use of low-temperature combustion and premixed combustion, respectively.

For premixed combustion, the fuel and oxygen must be thoroughly mixed prior to ignition. In the MK combustion concept, sufficient mixing time is secured by prolonging the ignition delay, and dispersion of the injected fuel is promoted to accomplish premixed combustion. The fuel injection timing is retarded so as to correspond to the prolonged ignition delay. A toroidal combustion chamber shape has been adopted for the purpose of promoting dispersion of the injected fuel outside the piston cavity. Additionally, a higher swirl ratio is generated to suppress the formation of HCs and soluble organic fraction (SOF). Experimental results have further confirmed that this combustion system is effective in reducing cooling losses [8,9]. It thus also incorporates a measure to counteract the deterioration of fuel consumption due to a decline in the degree of constant volume which is a side effect induced by retarding the fuel injection timing.

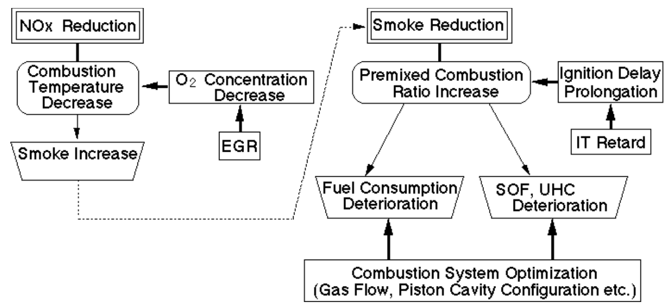


Figure 2. Schema of Modulated Kinetics (MK) Combustion

CHARCTERISTICS OF COMBUSTION AND EXHAUST EMISSIONS WITH MK COMBUSTION

COMBUSTION PHOTOGRAPHS – The main specifications of the single-cylinder test engine used in the experiments are given in Table 1. Combustion conditions were observed on the basis of high-speed photographs to confirm that the MK concept works to promote low-temperature, premixed combustion in a DI diesel engine. Photographs of MK combustion are compared in Fig. 3 with those of the conventional DI combustion process, typified by no EGR and a standard injection timing and swirl ratio. The heat release rate curves measured for each combustion process are also given in the figure.

Looking at the heat release rates, it is seen that the onset of heat release with the MK concept was plainly later than for the conventional combustion process, owing to the large retardation of injection timing. Another characteristic of MK combustion is the low heat release rate following the onset of heat release. This is attributed to the low rate of increase in cylinder pressure, which is thought to lead to a reduction of combustion noise. Although the initial heat release rate was low with the MK concept, combustion subsequently proceeded vigorously and the overall combustion period was virtually comparable to that of the conventional combustion process. Moreover, the general shape of the heat release rate curve for the MK concept shows a single stage of entirely premixed combustion. This is in clear contrast to the two-stage profile observed for the standard DI process, which is divided between an initial stage of premixed combustion and the main stage of diffusion combustion.

In the combustion photographs for the MK concept, virtually no clear sign of a brilliant flame is observed throughout the entire combustion period. By analogy with the high transparency of the flame, this is taken as proof not only of the weak luminous intensity of the flame but also of its low soot concentration on account of the low combustion temperature. Although the reduced combustion temperature cannot be substantiated directly from the photographs, they are thought to confirm a more advanced state of premixing, which was the original aim.

Table 1. Specifications of Test Engines

Engine Type		Single Cylinder Direct Injection
Intake System		Supercharged System
Bore × Stroke		ϕ 85 mm × 86 mm
Displacement		488 cm^3
Compression Ratio		18 : 1
Swirl Ratio		3 ~ 5
Injection System	Pump	High Pressure VE
	Nozzle	ϕ 0.22 mm × 5 VCO

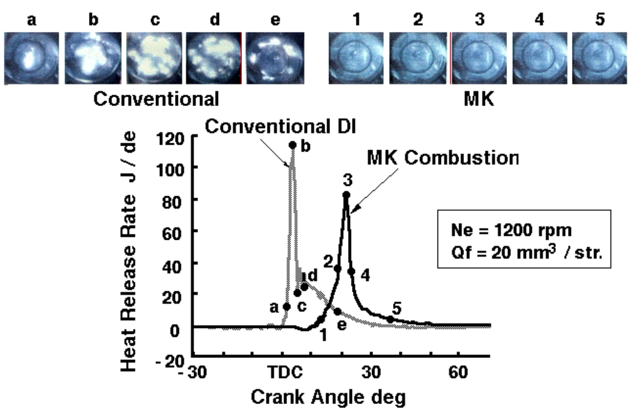


Figure 3. Comparison of Heat Release Rate and Combustion Photograph

PERFORMANCE CHARACTERISTICS – The effect of each combustion factor in the MK concept on exhaust emissions and thermal efficiency is shown individually in Fig. 4. With a lower oxygen concentration, NOx emissions were dramatically reduced by approximately 90%, and retarded injection timing reduced the smoke level markedly. Moreover, it is seen that the higher swirl ratio played a part in reducing smoke and unburned HC emissions. Figure 4 shows the effect of each combustion factor on thermal efficiency. With a lower oxygen concentration, which has a pronounced effect on reducing NOx emissions, the thermal efficiency improved, however the thermal efficiency was deteriorated with retarded injection timing. A higher swirl ratio improved the thermal efficiency over the level of ordinary combustion.

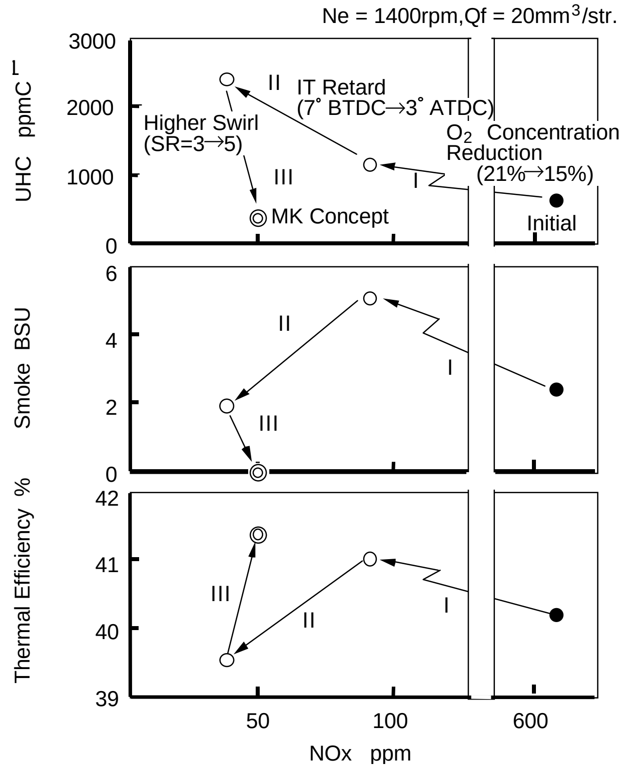


Figure 4. Effects of Each Combustion Factor on Exhaust Emissions and Thermal Efficiency

SECOND GENERATION OF MK COMBUSTION

CHALLENGES FOR MK COMBUSTION – The foregoing discussion has presented the fundamental characteristics of the low-temperature, premixed MK combustion process, based on experimental results obtained with simulated EGR gas. Tests conducted with a multi-cylinder engine using actual EGR gas also verified that MK combustion could be achieved in the low-load region in nearly the same manner as with the single-cylinder engine and the simulated EGR gas. The first generation of the MK combustion system was successfully implemented in a new four-valve-per-cylinder DI diesel engine (YD25) that was put on the market in June 1998 [10].

The application of MK combustion over a wide operating range is seen as an effective way to improve the emission, noise and vibration performance of small DI diesel engines for the 21st century. Two essential conditions for accomplishing MK combustion are the use of heavy EGR and the complete injection of all fuel prior to ignition. The region of application for the first-generation MK combustion system is shown schematically in Fig. 5 along with the target for the second-generation system. In the high-load region where the EGR gas temperature rises, MK combustion cannot be accomplished with the first-generation system because the ignition delay is shortened. The target set for the second-generation system aimed at reducing exhaust emissions further is to accomplish MK combustion at least throughout the entire 10-15 test mode region corresponding to the range of everyday driving.

In trying to apply MK combustion to the high-load region, it is predicted that two problems will have to be resolved, as outlined in Fig. 6. The first problem is that the ignition delay is shortened by the higher temperature of the EGR gas. The second problem is that the injection duration is prolonged by the greater quantity of fuel injected. The multiplied effects of these two problems make it impossible to complete the injection of all fuel prior to ignition, which is one of the necessary conditions for accomplishing premixed combustion.

Consequently, as indicated in the figure, there are two approaches that can be considered for expanding the MK combustion region to the high-load range. One approach is to prolong the ignition delay and the other approach is to shorten the injection duration. The fundamental objective of prolonging the ignition delay is to lower the gas temperature of the combustion field at top dead center (TDC) of the compression stroke. Specific ways of accomplishing that objective include cooling the EGR gas and lowering the compression ratio. On the other hand, the injection duration can be shortened with high-pressure injection or a larger nozzle hole, among other approaches.

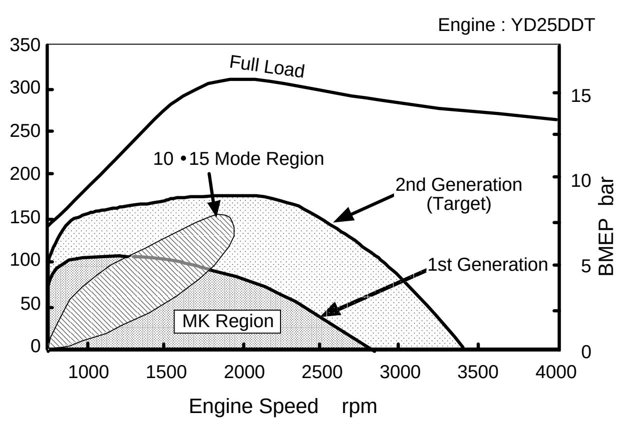


Figure 5. MK Combustion Region of First generation (YD25DDT) and Target

RELATIONSHIP BETWEEN IGNITION DELAY AND INJECTION DURATION – The specifications of the four-cylinder DI diesel engine used in the experiments are given in Table 2. An EGR gas cooler was provided in the EGR pipe running from the exhaust turbine inlet to the intercooler exit downstream of the intake air compressor. This EGR gas cooler was a water-cooled system that allowed the water circulation volume and water temperature to be adjusted. A piezoelectric sensor was fitted to the cylinder head to measure the cylinder pressure. Moreover, a dilution tunnel was used to measure PM emissions. A common rail injection system was adopted which allowed the injection pressure to be adjusted as desired, making it possible to achieve high-pressure injection even in the low speed range.

In order to expand the MK combustion region to the high-load range under a condition of heavy EGR, the ignition delay must be longer than the injection duration. The effects of high-pressure injection, a reduced compression ratio and EGR gas cooling, which were the approaches taken here to expand the MK combustion region, on the relationship between the injection duration and ignition delay are shown in Fig. 7. These results were obtained near the maximum load level of the 10-15 test mode under the conditions of a constant injection timing and EGR rate. For the baseline engine with the first-generation MK combustion system, the difference between the injection duration and the ignition delay was a short interval of slightly more than ten crank angle degrees. This difference was progressively shortened by the application of each approach, and the combination of all three approaches resulted in an ignition delay that was longer than the injection duration. Under these conditions, it was then confirmed that the ignition delay exceeded the injection duration for all of EGR rates described in the following section.

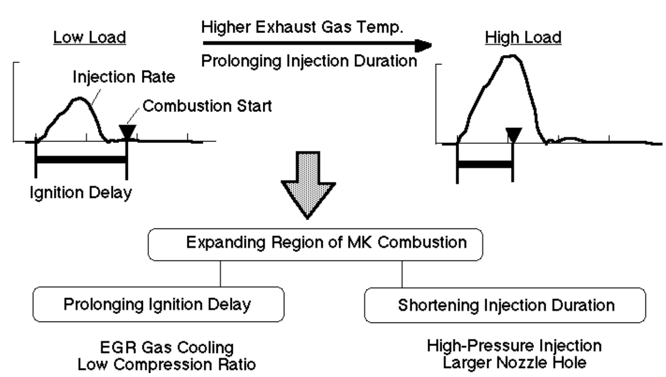
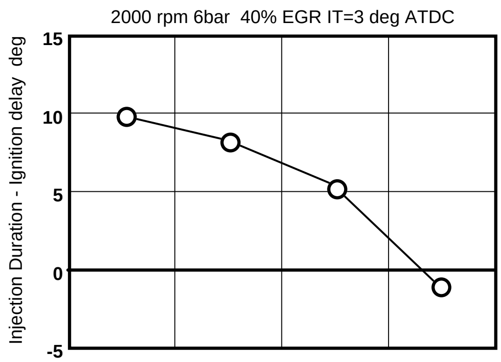


Figure 6. Approach for Expanding the MK Combustion Region

Table 2. Specifications of Test Engine

Engine Type		4 - Cylinder Direct Injection
Intake System		Turbocharged System
Bore × Stroke		ϕ 89 mm × 100 mm
Displacement		2488 cm^3(622 cm^3/cyl)
Compression Ratio		17.5:1 ; 16.0:1
Combustion Chamber		Toroidal
Swirl Ratio		3.6 ～ 10.0
Injection System	Pump	Common Rail System
	Nozzle	ϕ 0.23 mm × 5



Injection Pressure	700	1600	←	←
Compression Ratio	17.5	←	16	←
EGR Cooler	without	←	←	with

Figure 7. Effects of Injection Pressure, Compression Ratio and EGR Cooling on the Relation between Injection Duration and Ignition Delay

COMBUSTION CHAMBER SPECIFICATION – The foregoing discussion has shown that a combination of a lower compression ratio, high-injection pressure and EGR gas cooling can prolong ignition delay than injection duration in the high-load region. However, it was feared that a lower compression ratio might cause HC emission performance to deteriorate in cold-condition. Ordinarily, the effective approach to reduce HC emission in cold-condition is the avoiding fuel-cavity wall interaction. A small nozzle hole is one way to avoid the fuel-wall interaction, however this leads prolonging injection duration, which is an opposite tack of MK combustion. So, the large cavity diameter is used to avoid HC emissions in cold-condition.

Fig. 8 and Table 3 shows the piston configuration used this test. Compression ratios were maintained 16. Fig. 9 compares HC emissions as function as coolant temperature. HC emissions under hot-condition did not change on account of the large cavity diameter. Under the cold-condition, coolant temperature was 313k, HC emission with the large cavity diameter was significantly reduced. According to this results, the following experiments were conducted using the large cavity diameter.

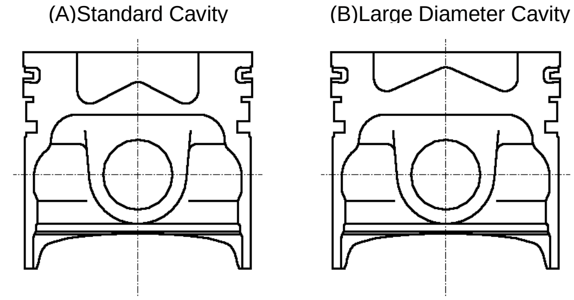


Figure 8. Sections of Test Pistons

Table 3. Specification of Test Pistons

	(A)	(B)
Cavity Shape	Troidal	
Cavity Diameter (Cavity Diameter / Bore)	47.2 mm (53%)	56.1 mm (63%)
Cavity Depth	19.8 mm	15.0 mm

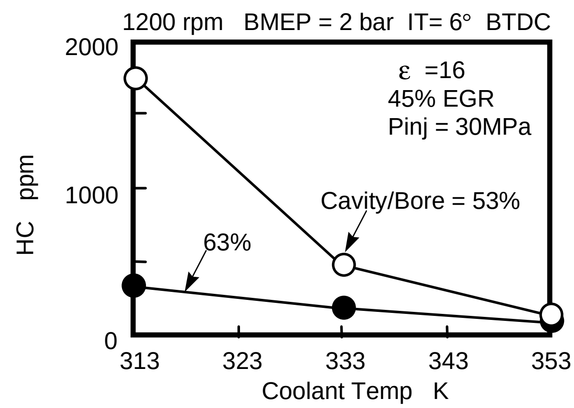


Figure 9. Effect of Enlarging Cavity Diameter on Cold-Start HC Emission

EMISSION PERFORMANCE IMPROVEMENT OF SECOND GENERATION MK COMBUSTION

SMOKE CHARACTERISTICS – The foregoing results indicated that the combination of low compression ratio, EGR cooling and high injection pressure could make the ignition delay longer than the injection duration. An attempt was then made to achieve MK combustion over nearly the entire load range by substantially changing the ignition delay as a result of cooling the EGR gas. The results obtained are shown in Fig. 10, which presents a map indicating the effect on the smoke concentration of the difference between the injection duration and the ignition delay and the excess air ratio λ. The data were obtained under conditions of an engine speed of 2000 rpm and 6 bar break mean effective pressure (BMEP). It is seen that smoke increased with a smaller λ value in the region of a short ignition delay, i.e., the area where the horizontal axis values are greater than zero. The smoke level shows an especially sharp increase at λ values below 1.2. By contrast, the smoke level decreased in the region where the ignition delay exceeded the injection duration, and even at λ values below 1, the smoke level was less than 1 BSU. These results indicated that smoke generation can be suppressed even in the region near a stoichiometric mixture ratio by making the ignition delay longer than the injection duration.

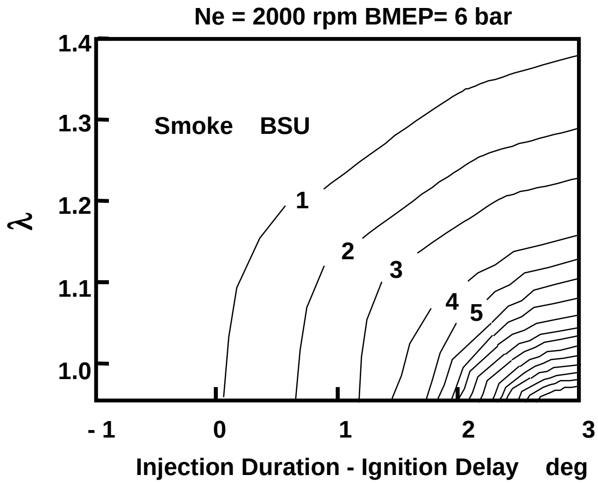


Figure 10. Effects of Prolonging Ignition Delay on Smoke Level

COMPARISON OF PERFOMANCE BETWEEN CONVENTIONAL AND MK COMBUSTION – Figure 11 compares the emission performance between MK combustion, which make the ignition delay longer than the injection duration, and conventional combustion. The injection pressure and air excess ratio of both specification were kept 1600 bar and 1.3. MK combustion produces NOx emissions that are below 0.3 g/kWh without significant increase of PM and fuel consumption. In contrast, it is seen that the PM levels with conventional combustion increase sharply when NOx level fall below 2 g/kWh. As a results of this increase of PM, it is difficult that NOx level with conventional combustion is reduced below 1 g/kWh.

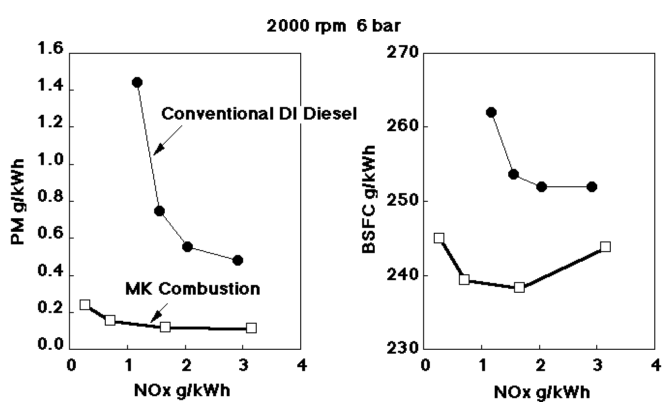


Figure 11. Comparison of NOx, PM and BSFC between Conventional and MK Combustion

The NOx reduction rate and particulate emissions on conventional and MK combustion are compared in Fig. 12. The conventional combustion was run with several injection pressure levels, from 700 to 1600 bar. Looking at the NOx reduction rate (NOx/NOx baseline), NOx reduction rate of MK combustion is over 98% and the limit of NOx reduction rate with conventional combustion is from 90 to 92 %.

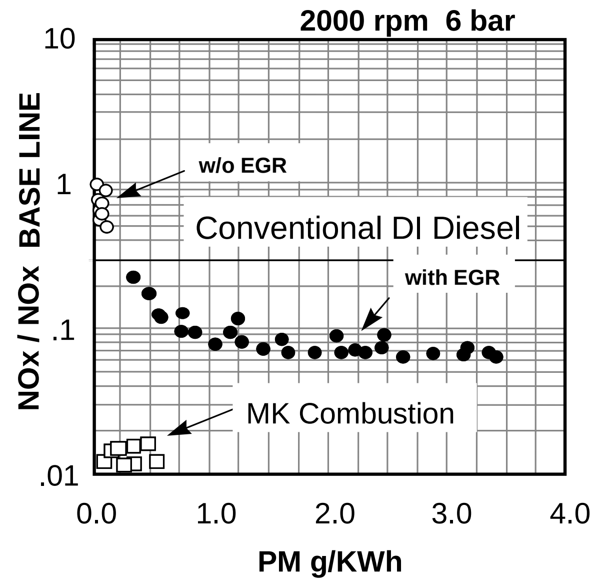


Figure 12. Emission Comparison: MK Combustion vs. Conventional DI Diesel

The heat release rate of MK combustion and conventional obtained under a condition of the lowest oxygen concentration is shown in Fig. 13. The heat release rate curve shows a single-stage profile with gradual heat release in the initial combustion period. This type of profile characterizes the heat release rate of MK combustion. From this result as well, it is concluded that the attainment of MK combustion worked to reduce the smoke level.

The extension of MK combustion to the high-load range in this study showed that NOx emissions could be reduced by more than 98% over the entire range of everyday driving without having a large adverse effect on smoke formation and fuel consumption. Furthermore, the second-generation MK combustion system with the excess air ratio limit expanded to near the stoichiometric air-fuel ratio level without increase of smoke has a latent possibility for using the NOx catalyst.

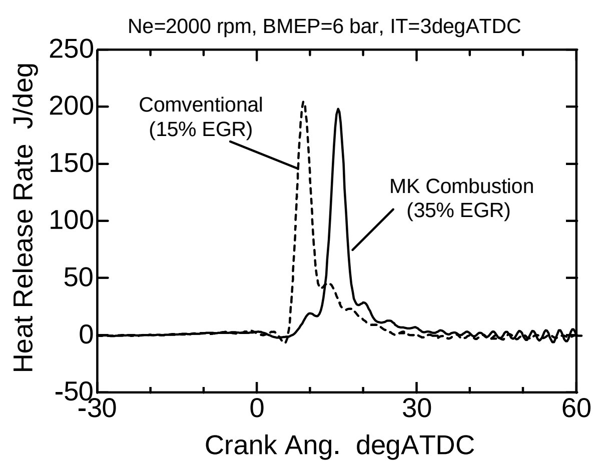


Figure 13. Comparison of Heat release Rates between Conventional and MK Combustion

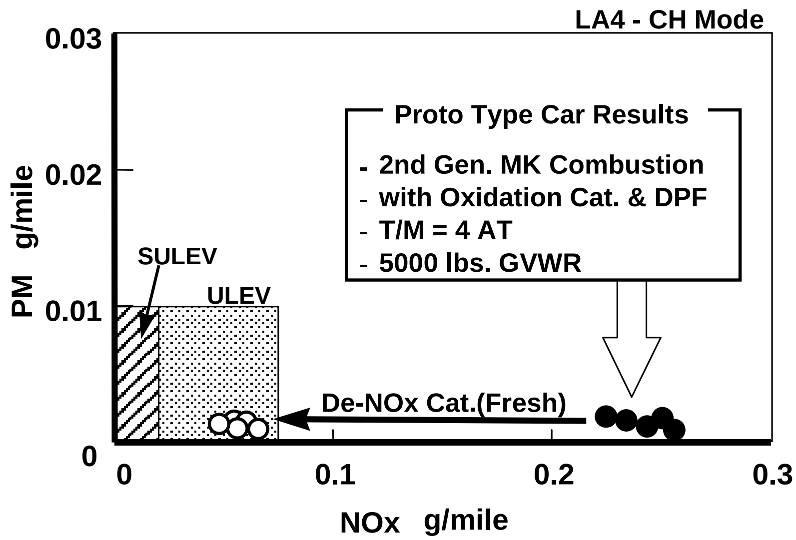


Figure 14. Test Car Results with second-generation MK Combustion and 5way Catalyst

The test car results with second-generation MK combustion and 5way catalyst are shown in Fig. 14. The 5way catalyst consists of the oxidation catalyst, particulate filter and De-NOx catalyst. In this experiment, NOx adsorber is used for De-NOx catalyst. The sulfur content of the fuel is maintained below 10ppm. According to the test car results, the combination of second-generation MK combustion and 5way catalyst has the possibility of meeting the ULEV emission (NOx<0.07g/mile, PM<0.01g/mile) with 5000 lbs. gross vehicle weight rating (GVWR).

At the present time, however, this system is still at the research level and there are numerous issues that remain to be resolved, including the cooling capacity of the EGR gas cooler and measures for controlling cold-start HC emissions. Nevertheless, the fact that this study confirmed a diesel engine has the potential to achieve emission levels comparable to those of a gasoline engine is a significant result, even though it was obtained at the research level.

CONCLUSION

This paper has proposed a low-temperature, premixed combustion concept, referred to as the MK concept, which is designed to achieve simultaneous reductions in the NOx and smoke emissions of a small DI diesel engine. With the aim of expanding the MK combustion region, a multi-cylinder test engine was used to confirm the effect of combining a low compression ratio, high-injection pressure and EGR gas cooling. The results made the following points clear.

1. The combination of a low compression ratio, high-injection pressure and EGR gas cooling can make ignition delay longer than injection duration.
2. In cold-condition, the large cavity is effective to avoid the increase of HC emission due to low compression ratio.
3. It was confirmed that the smoke concentration could be reduced to less than 1 BSU in the operating region near a stoichiometric air-fuel ratio with the ignition delay longer than injection duration.
4. NOx reduction rate of MK combustion is over 98% and the limit of NOx reduction rate with conventional combustion is from 90 to 92 %.

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