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Development of Direct Injection Gasoline Engine

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Toyota Motor Co.

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ABSTRACT

A new 2.0 ℓ DOHC 4-valve direct injection (DI) gasoline engine has been developed which features new technologies such as swirl intake ports to produce an optimum swirl in the cylinder by variable controlled swirl control valve, pistons with a concave combustion chamber, and high pressure fuel injection system to provide a fine fuel-air mixture cloud in the combustion chamber. These all help to control fuel-air mixture preparation and flame propagation under ultra lean, stratified combustion at partial loads. NOx emission is reduced by using an electrically controlled EGR system and an NOx storage-reduction catalyst. At higher loads, a homogeneous mixture is obtained with direct injection during the intake stroke. A seamless output torque transition between stratified charge and homogeneous charge condition is achieved by an electronic throttle control system.

It has been confirmed that a vehicle with this system successfully improves fuel economy while satisfying emission requirements.

INTRODUCTION

A DI type of gasoline engine has long been considered a method to achieve both high fuel economy and performance simultaneously. For more than fifty years, extensive studies have been made by many institutes and manufacturers [1-3]. The DI engine boasts the following advantages,

(1) High thermal efficiency because of lower pumping loss and heat loss;
(2) High volumetric efficiency and anti-knock characteristics because of lower temperature of charge air ; and
(3) High acceleration response and superior transient driveability even under cold temperature conditions because of the direct fuel injection into the cylinder.

On the other hand, there still remain several difficulties in:

(1) Control of the stratified mixture under wide engine operating conditions;
(2) Reducing smoke generation in higher load regimes;
(3) Reducing NOx emission during stratified charge operation; and
(4) Reducing the accumulation of deposits at the injection nozzle.

Recently, both growing attention towards energy saving and rapid progress in micro computers and sensor technologies have aroused the interests in DI systems [4-6].

In this paper, a newly developed 2.0 ℓ DOHC DI gasoline engine is introduced. This DI engine solved these above problems with new technologies such as helical intake ports with a swirl control valve, involute concave piston and high pressure fuel injection system. A sophisticated engine management system is also introduced including injection, ignition timing and throttle control. Further description is given about combustion characteristics, fuel economy and exhaust emission performance.

SYSTEM OUTLINES

Fig.1 shows a schematic view of the combustion chamber configuration and Table 1 shows specifications of the new DI engine. The new engine features three main items, as follows:

(1) Piston with involute shaped concave combustion chamber to control mixture formation and flame propagation;
(2) High pressure swirl fuel injector to realize precise control of fuel atomization and mixture formation; and
(3) Intake port with swirl control valve (SCV) to control in-cylinder gas motion and mixture location;

To realize high fuel efficiency, driveability and low exhaust emissions, three types of injection controls are employed for different combustion conditions, as shown in Fig.2.

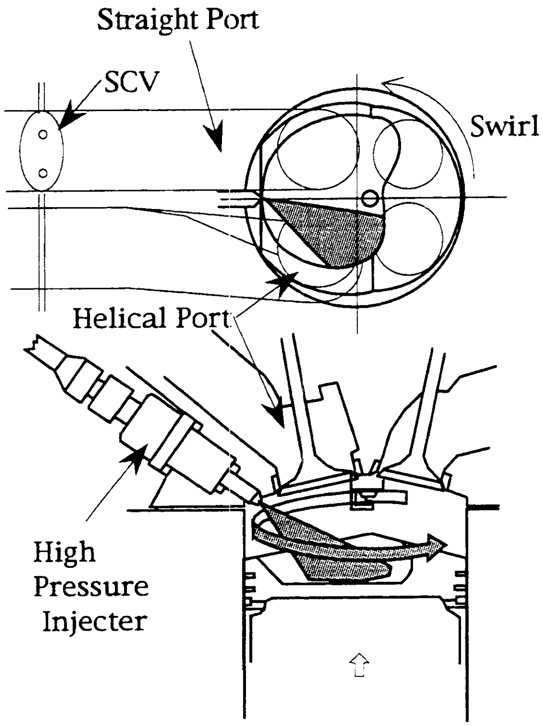


Fig.1 Combustion chamber configuration

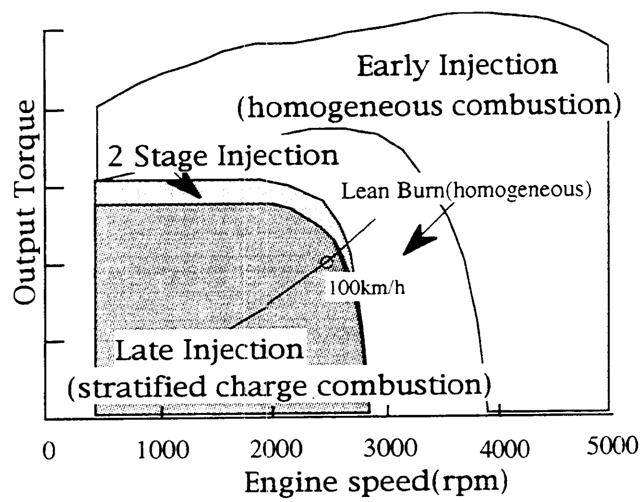


Fig.2 Combustion strategy of TOYOTA direct injection system

Table 1 Engine specifications

Displacement	1998cc
Bore * Stroke	86 * 86 mm
Type	In-line, 4-Stroke
Valves per Cylinder	4
Compression Ratio	10.0: 1
Intake Port	Helical + Straight
Fuel Pressure	12MPa
Fuel Supply	High Pressure Swirl Injector
Fuel	91RON

LATE INJECTION - At partial loads, ultra-lean stratified combustion is obtained with direct injection into the cylinder during the compression stroke. In this phase, fuel is injected before ignition by a pre-determined interval, so that the injected fuel is diffused and vaporized enough to be ignited.

EARLY INJECTION - At higher loads, a homogeneous mixture is intended with direct injection during the intake stroke, in order that fuel is thoroughly diffused in the whole cylinder.

TWO STAGE INJECTION - In between stratified and homogeneous charge operations, fuel is supplied during both intake and compression stroke. Thus, a semi-stratified mixture is obtained to keep smooth torque transition from ultra-lean operation to lean or stoichiometric mixture operation area.

A non-continuous throttle opening requirement exists between the three air/fuel mixture areas. Actually, wider throttle opening is required in stratified operations compared to that in homogeneous operation, because the ultra-lean (AFR > 30) mixture is supplied in the former condition. An electronic throttle control (Drive-by-Wire) system is employed to meet this requirement. Besides this, rich mixture supply control for the NOx catalyst and vacuum control to the brake system also require a sophisticated throttle control.

As for NOx emissions which are inherently high with stratified operation, an electrically controlled EGR system is employed to reduce engine-out emissions. An NOx storage-reduction three way catalyst is also employed for after treatment. The NOx catalyst is located under the floor of the vehicle to keep the catalyst temperature around 250 to 450 ℃ (where this catalyst shows the highest conversion efficiency) in usual driving conditions in Japan.

In addition, a close-coupled three way catalyst is adopted to meet HC emission requirements, because the exhaust gas temperature remains quite low while driving under ultra-lean stratified mixture conditions.

ENGINE MANAGEMENT SYSTEM - Fig.3 shows a schematic diagram of the new DI engine control system. In most management systems, the method of determining the output signals (fuel quantity, injection timing) is the most critical issue. Generally, electronic fuel injection systems employ an air flow sensor or an intake manifold pressure sensor to deduce the amount of intake air in each cycle, because that is the most basic information to describe the operating conditions of the gasoline engine. With the new DI engine, nearly unthrottled operation is realized in stratified charge mixture conditions. Thus, information about the amount of intake air has less importance

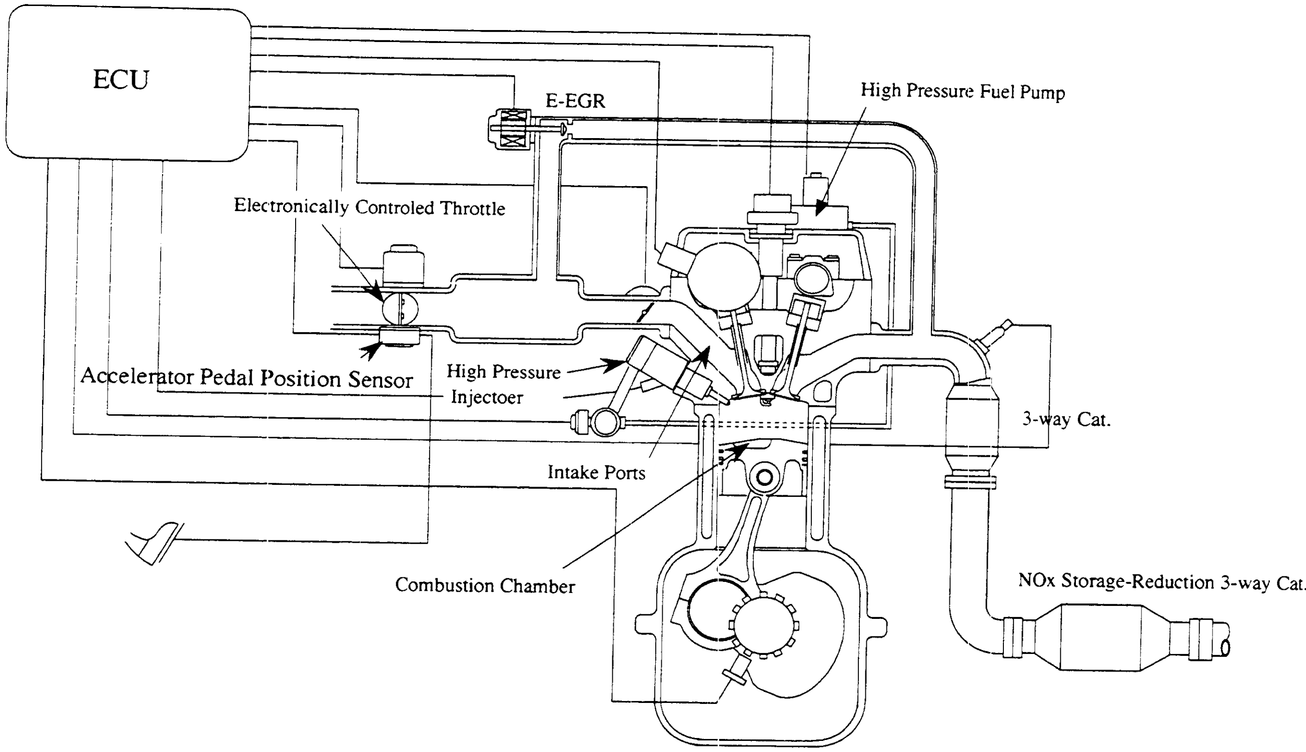


Fig. 3 Schematic diagram of DI system

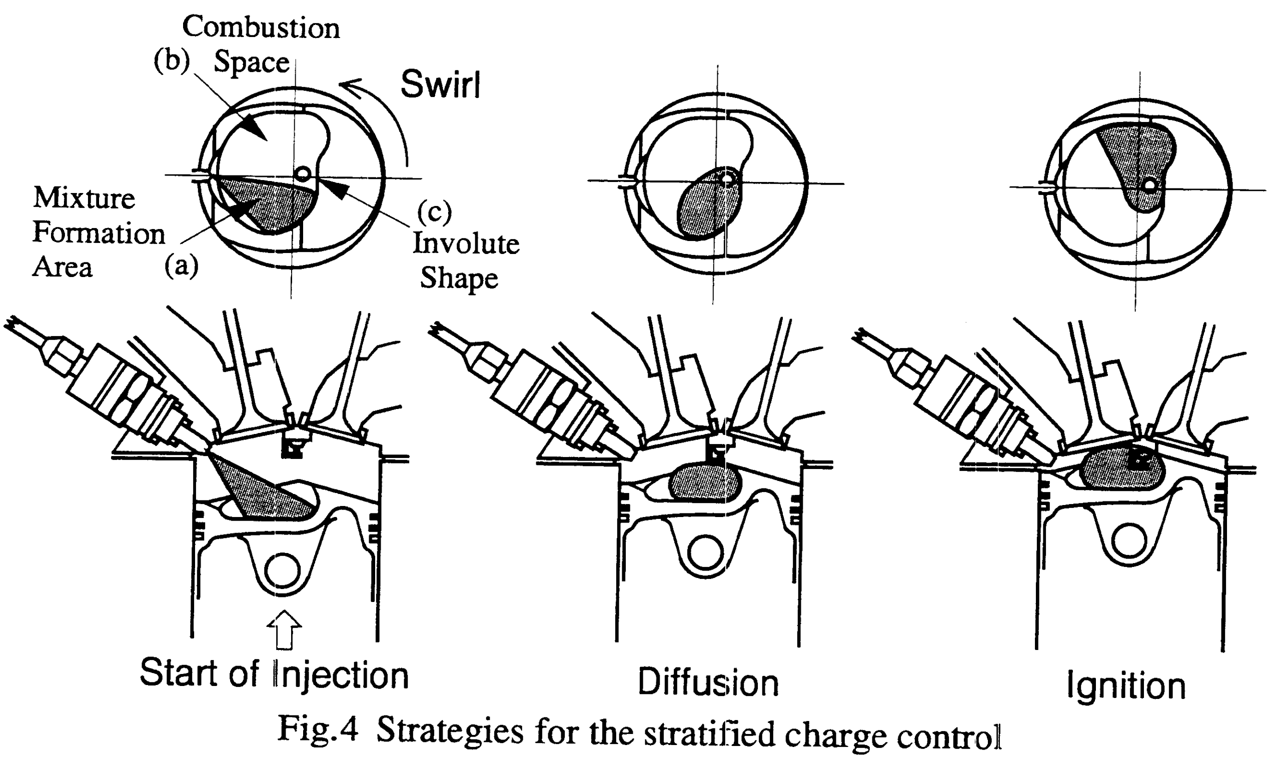


Fig.4 Strategies for the stratified charge control

in actual engine operation. Under stratified charge condition, the accelerator pedal opening angle, rather than the intake manifold pressure, is the most important information for determining the quantity of injected fuel. This method is quite similar to a diesel engine control system. All the other operating parameters are determined from the quantity of injected fuel and the engine speed.

STRATEGIES FOR STRATIFIED CHARGE CONTROL

COMBUSTION CHAMBER DESIGN - To achieve stratified charge with a gasoline direct injection engine, the most important task is to provide a combustible mixture formation at the correct timing and at the correct location relative to the spark plug.

Fig.4 shows the strategies employed for stratified charge control in the new DI engine. A uniquely shaped cavity in the piston is used. The narrower zone (a) of the cavity - located in the upper flow of the swirl motion - is mainly designed for the mixture formation area, while the wider zone (b) is mainly for the combustion space and designed to promote a rapid mixture diffusion. The involute shape (c) is designed so that the vaporized fuel flows towards the spark plug. The depth of the cavity and angle of the cavity wall are also optimized for proper mixture formation and for preventing the undesirable diffusion of air-fuel mixture out of the cavity.

Fuel is injected during the compression stroke in the direction so as not to wet the spark plug. The fuel impinges on the cavity wall and flows along the concave surface to the spark plug by force of swirl and penetration by the injected pressure. In this stage, fuel is vaporized by heat transfer from the ambient air and the piston wall.

HELICAL INTAKE PORTS WITH SCV - Through extensive studies on the mixture and turbulence control with lean burn technologies at Toyota [7,8], a new set of helical intake ports with SCV(swirl control valves) has been developed for the DI engine. These ports consist of a helical port and straight port, which are fully separated (Fig.1). The SCV is located in the upstream of the straight port. These valves are driven by a DC motor so that the desired valve opening angle is available corresponding to the engine operating conditions. The swirl ratio is about 2.1 when the SCV is fully closed. An SCV opening map is shown in Fig.5. In the early injection pattern (used for higher loads), the SCV is fully closed to obtain intense swirl, which achieves a homogeneous lean mixture. On the other hand, in the late injection pattern (for partial loads), the SCV is partially open to achieve optimum mixture formation by controlling the swirl intensity and the direction of the injected fuel flow.

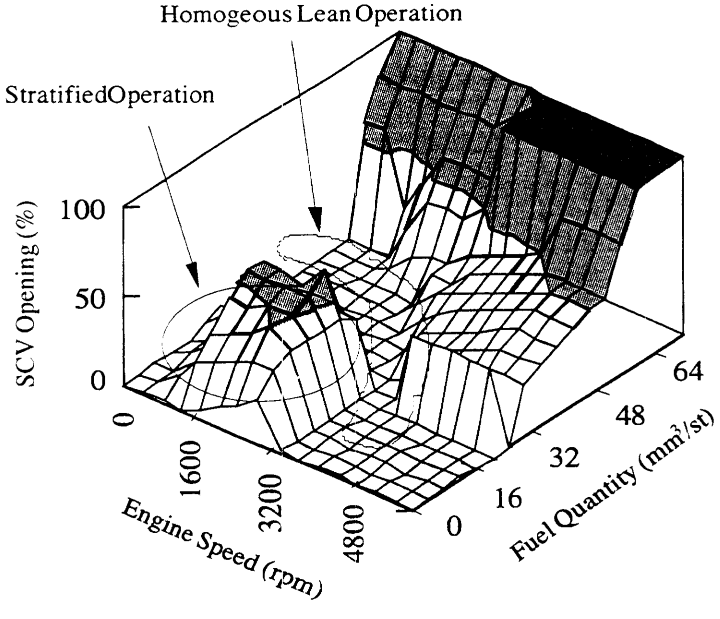


Fig.5 SCV operating map

HIGH PRESSURE FUEL INJECTION SYSTEM

High fuel injection pressure is necessary because fuel flow must penetrate against high environmental pressure in a short period during the compression stroke. Fuel atomization is also enhanced by high pressure injection [9]. The newly developed high pressure swirl injector (Fig.6) meets these requirements by employing an injection pressure of 12 MPa. The direction of injection is offset from the spark plug to allow enough time for the fuel to vaporize.

Fig. 7 shows a photo of fuel spray under atmospheric pressure taken 3 msec after start of injection. It is confirmed that the fuel spray is highly atomized realizing narrow cone angle, which means that there is much space for vaporizing without risk of plug carbon fouling. Fig. 8

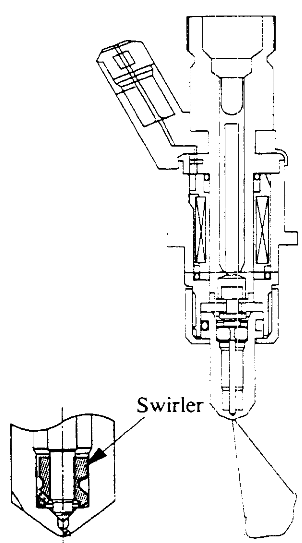


Fig.6 Swirl injector

12MPa
3ms after injection

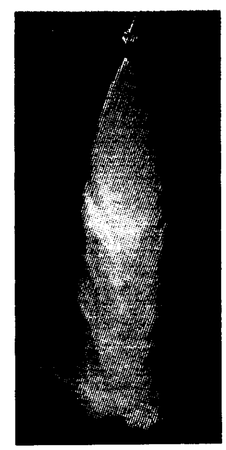


Fig.7 Spray shape

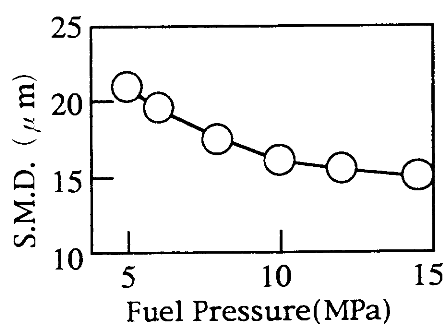


Fig. 8 Droplet size of injection spray

shows the relation between fuel spray droplet size and injection pressure. The Sauter mean diameter (SMD) of the droplets gradually increases for decreasing injection pressure below 8 MPa. Fig. 9 shows the relation between fuel pressure and fuel consumption improvement over port injected homogeneous stoichiometric operation. It is clearly shown that for engine speeds of 1600-2400 rpm, the fuel consumption improves as the fuel pressure increases, but at 1200 and 800 rpm the best efficiency is obtained at 8 MPa. For the DI engine, injected fuel must impinge on the sweet spot in the chamber of the piston which is traveling rapidly towards TDC. At higher engine speeds, short injection duration with higher injection pressure ensures a well stratified mixture around the spark plug without unnecessary diffusion in the chamber. On the contrary, at lower speeds, lower injection pressure enables fuel spray to have longer traveling time to the piston, thus vaporization by the heat transfer from ambient air is promoted.

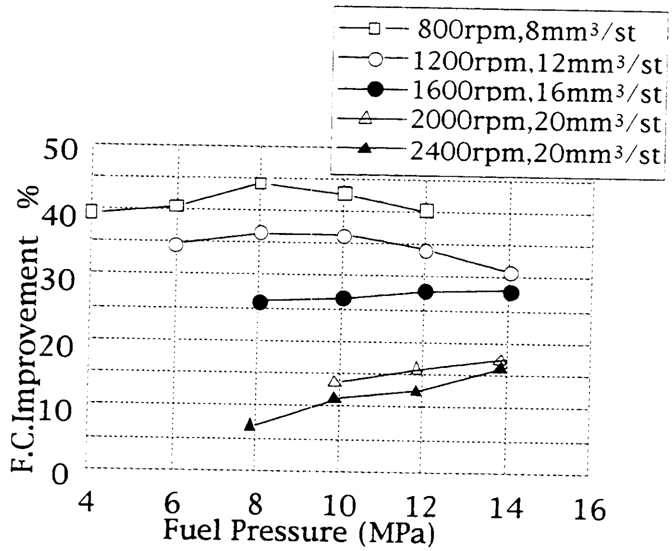
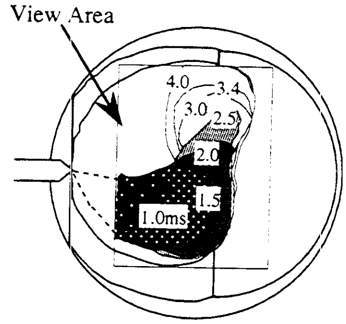


Fig.9 Effects of fuel pressure on fuel consumption improvement

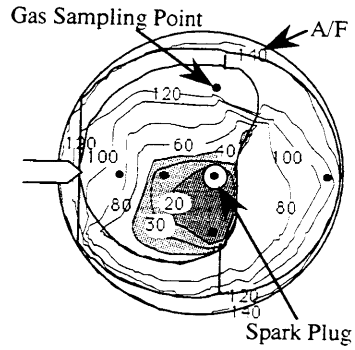
MIXTURE FORMATION

Mixture formation during stratified charge operation was investigated by two methods. Fig. 10 shows in-cylinder fuel behavior taken by CCD camera through a plug hole at 1.0 to 4.0 msec after start of injection . It is clear that the fuel spray reaches the mixture formation area (lower) and diffuses towards the combustion area (above) as intended. Fig. 11 shows mixture distribution contours estimated by the in-cylinder gas sampling results, where the fuel injection was at 80 deg. before TDC of the compression stroke. The gas was sampled at 16 deg. BTDC (just before the ignition timing). As can been seen, the mixture is well stratified, ensuring rich mixture around the spark plug.



1200rpm*20mm^3/st
Injection Timing BTDC70℃A

Fig.10 Mixture motion during stratified charge operation



2400rpm*20mm^3/st
Injection Timing BTDC80℃A
Gas Samping Timing BTDC16℃A

Fig.11 Mixture distribution by in-cylinder gas sampling

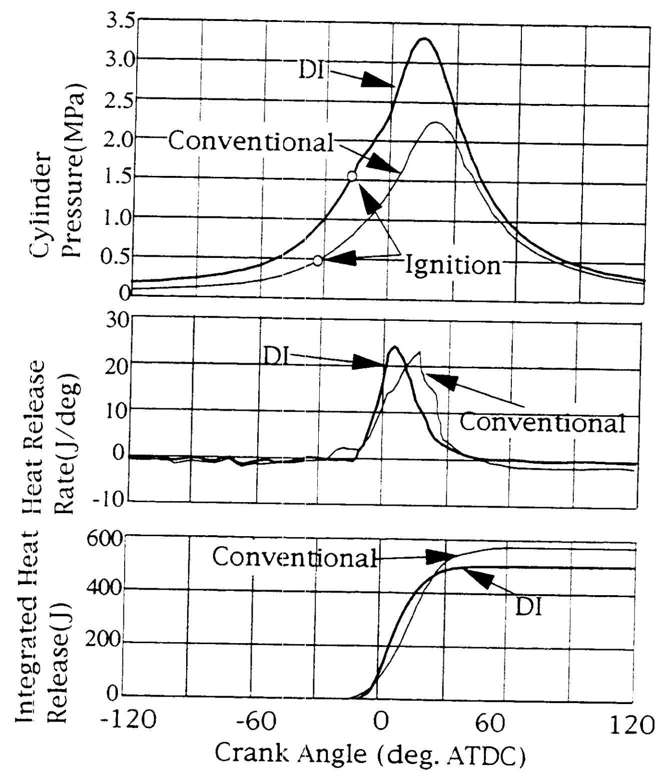


Fig.12 Combustion analysis by pressure indicator diagram

COMBUSTION CHARACTERISTICS

PARTIAL LOAD PERFORMANCES - Fig. 12 compares combustion characteristics between the DI engine and conventional gasoline engine. The former runs under air fuel ratio of 27 and latter by 14.7 (stoichiometric). As can been seen, the combustion rate is rather fast and stable with the DI engine although it runs by almost twice as lean mixture. Higher pressure is observed at the beginning of compression and also at the peak with the DI engine because it runs with much more inducted air. Accordingly, the DI engine realizes greater fuel efficiency with lower pumping losses compared to the conventional engine.

Flame propagation of the new DI engine was visualized by high speed photography through a special quartz piston from the bottom view of the cylinder (Fig.13). These photos were taken at the moment of 10, 50 and 90% mass fraction burned. The upper three photos were taken during stratified operation with an air fuel ratio of 40. It is shown that the flame mainly propagates downstream of the swirl in the combustion zone as intended. In the early stage of combustion, stable flame propagation is confirmed by observing that a luminous flame is surrounded by a blue flame. Due to the configuration of the piston (larger combustion space is provided compared to the mixture formation area - see Fig.4), flame propagation is promoted by mixing with an air-rich environment as the time elapses. For comparison, flame propagation with homogeneous stoichiometric mixture operation is shown in Fig.13 (bottom photos), where fuel is injected during the intake stroke. In this case, flame propagation is also promoted mainly in the combustion zone at first, and then diffused all over the cylinder. The fact that the most of the chamber is filled with blue flame suggests that the homogeneous charge is successfully realized, although almost 2.5 times the amount of fuel is supplied compared to the stratified operation.

The lean combustion limit and NOx emissions with stratified operation was investigated (Fig. 14). The test conditions are 1200 rpm, 12 mm^3 injected fuel, and the air-fuel ratio is given by a function of a throttle opening angle

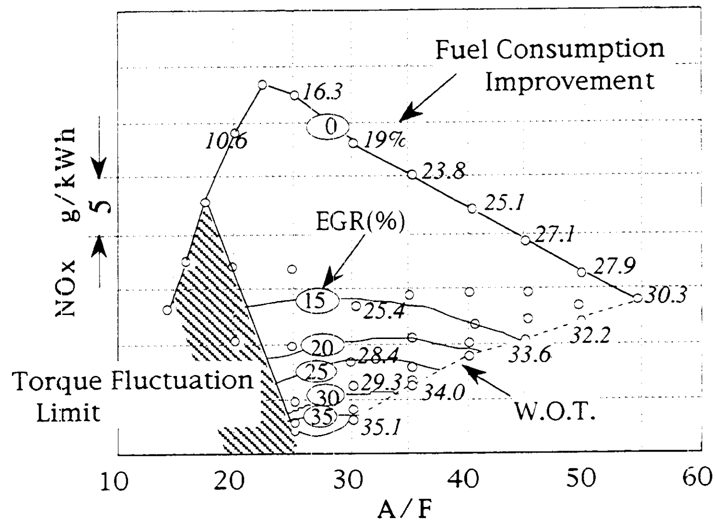


Fig.14 Combustion characteristics with stratified operation (1200rpm,12mm^3/st)

and EGR rate (circled in the figure). The numbers in italic indicate fuel consumption improvement over the homogeneous stoichiometric operation base engine, and the shaded region shows torque fluctuation limit (misfire caused by excessively rich mixture). It is confirmed that the engine still runs stably at WOT with an air-fuel ratio as high as 55, and at this point fuel consumption is improved by 30.3%. NOx is reduced but not as significantly as with a premixed lean burn engine. This fact indicates that the stratified rich mixture is well preserved around the spark plug.

MEDIUM LOAD PERFORMANCE - Stratified mixture operation is restricted under high load by smoke generation because excessively rich mixtures exist around the

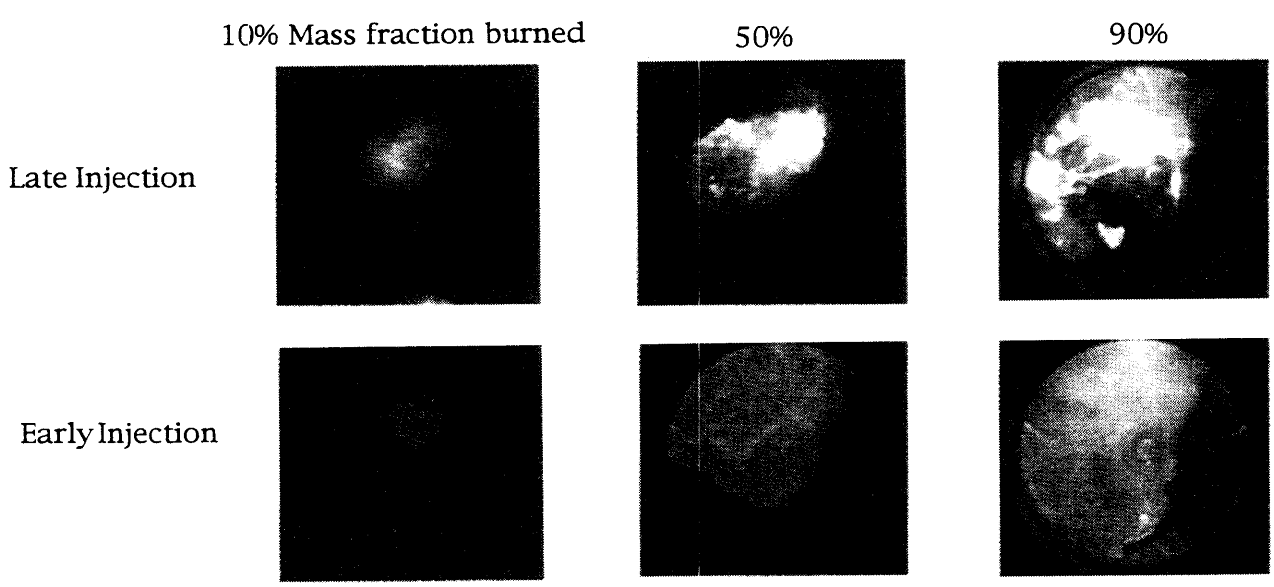


Fig.13 Typical process of flame propagation for late and early direct injection

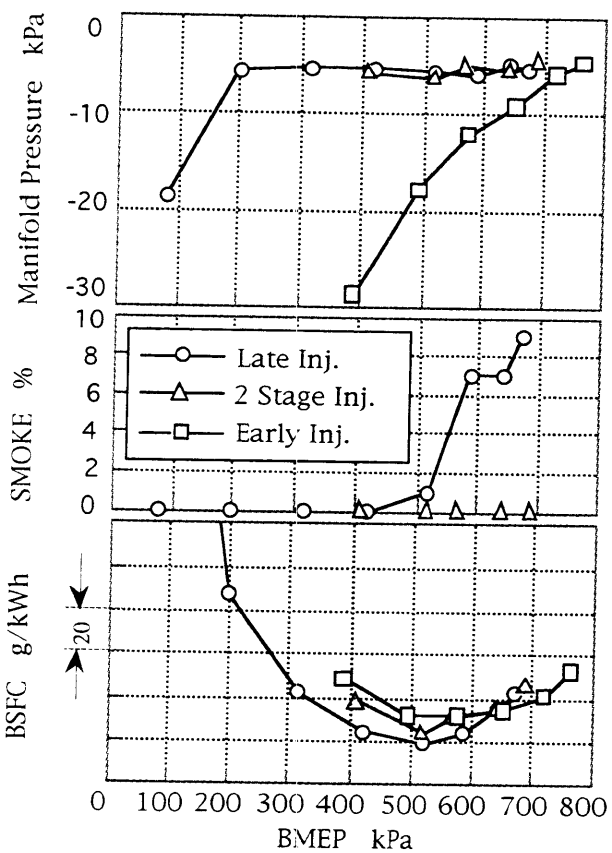


Fig.15 Smoke free operation with 2-stage injection (1200rpm)

spark plug. The smoke generation problem can be solved by employing homogeneous charge control at higher loads. The required air as well as the throttling angle, however, differ largely between that of homogeneous charge control and stratified control. This causes a discontinuity in the torque transition between these two operating regimes. To solve this problem, two stage injection operation is employed, where the fuel is injected first in the intake stroke and then again in the compression stroke. With this control, semi-stratified charge is realized and continuous torque character is obtained without smoke generation (Fig.15).

HIGHER LOAD OPERATION -- As mentioned earlier, homogeneous mixture operation is used at the high loads. Lean burn, stoichiometric and enrichment control are all used to realize low emissions and high output performance.

NOx REDUCTION WITH EGR AND CATALYST

As is the case with conventional engines including lean burn, EGR is also effective for NOx reduction on the gasoline DI engine. The effect of EGR on NOx reduction, fuel consumption and torque fluctuation is indicated in Fig.14. It is shown that both NOx reduction and fuel consumption improvement is realized as the EGR rate increases up to 35%. At this point, 88% of NOx reduction is obtained over stratified control without EGR, and 35.1% of fuel consumption improvement is obtained over homogeneous stoichiometric operation within allowable torque fluctuation.

Even with a large amounts of EGR, NOx reduction was not enough to satisfy the NOx emission requirement in

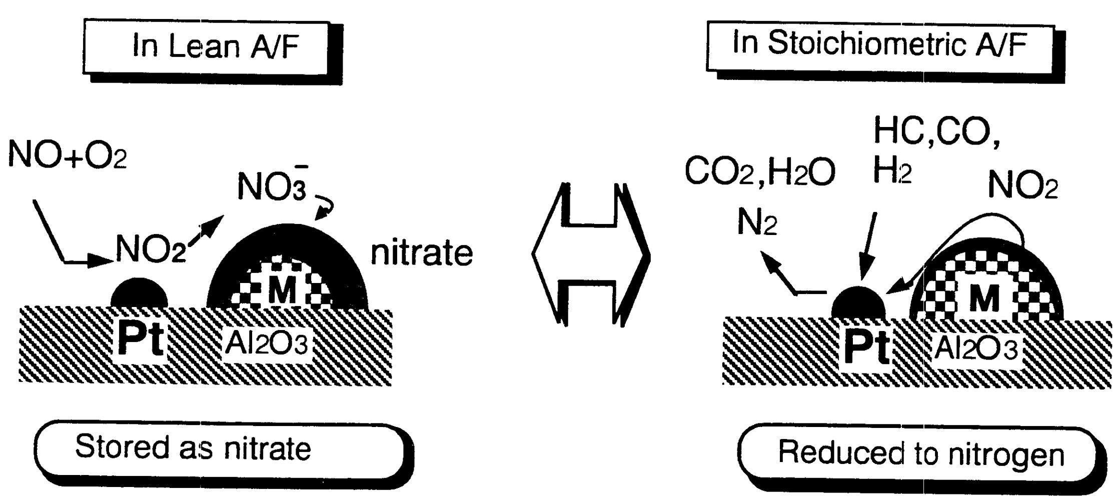


Fig.16 NOx storage-reduction mechanism

the Japanese 10-15 mode cycle. Homogeneous lean mixture operation without EGR is also employed in the higher load area. Therefore, an NOx reduction catalyst was employed. A new NOx reduction catalyst has been put into production since 1994 with Toyota lean burn engines in Japan [10]. The catalyst works with an NOx storage-reduction function. Actually, NOx is stored in the catalyst during lean operation, then the stored NOx is reduced to nitrogen in stoichiometric or rich operating conditions (Fig.16). With this type of catalyst, stoichiometric or rich mixture control is occasionally necessary even under average lean burn cruising conditions. As a consequence, the torque difference between these rich and lean burn conditions must be avoided. During homogeneous lean mixture control (where fuel is injected during the intake stroke), constant output torque is obtained by synchronized control of injection enrichment and spark timing retard. On the other hand, during stratified charge operation, this constant torque control is not only realized by fuel amount and spark timing control, but also by injection timing shift (compression to intake stroke), large throttle opening change and adjustments with other actuators (swirl control valves, EGR valve). Fig. 17 shows how rich mixture supply control is performed during stratified charge operation. The most significant changes appear in air fuel ratio (35 to 11) and injection timing. The transient phase (a) to (d) is set in between stratified and homogeneous control area to gradually smooth out the torque difference. Then fuel injection amount, spark timing and throttle angle are changed stepwise to avoid torque differences. The injection pattern is repeatedly switched from compression stroke to intake/compression stroke and intake stroke control.

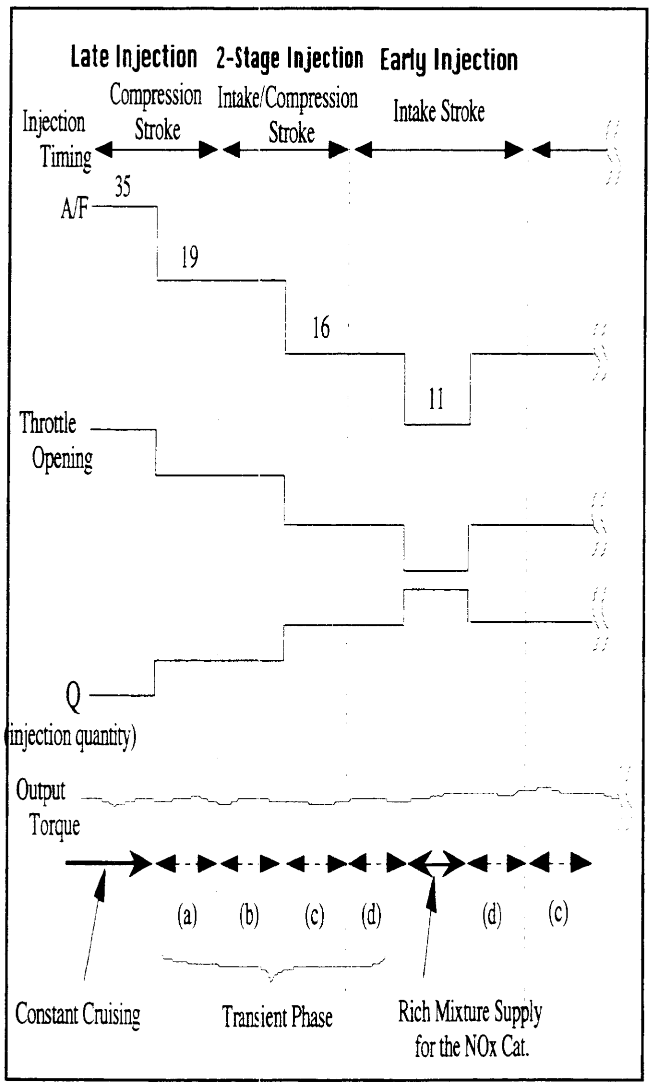


Fig.17 Rich mixture supply control for NOx catalyst

THROTTLE CONTROL SYSTEM

Theoretically, unthrottled operation is possible with stratified mixture in the partial load area. For several reasons, however, throttle control is necessary for an actual production engine. First, as mentioned before, NOx reduction with EGR is essential, and EGR requires an intake manifold vacuum derived by throttle control. Secondly, a conventional vacuum assisted brake system needs some vacuum at braking conditions. Thirdly, non-throttling operation at low load operation causes very low exhaust gas temperature, so purification of exhaust gas by catalytic converter becomes difficult. Lastly, and the most significant reason, is that even the DI engine with stratified operation must run under conditions such as cold starting and high load operations, which require homogeneous charge. Conventional mechanically-linked throttle systems have difficulty satisfying the wide-range of throttle opening requirements in these cases. For this reason, an electroni-

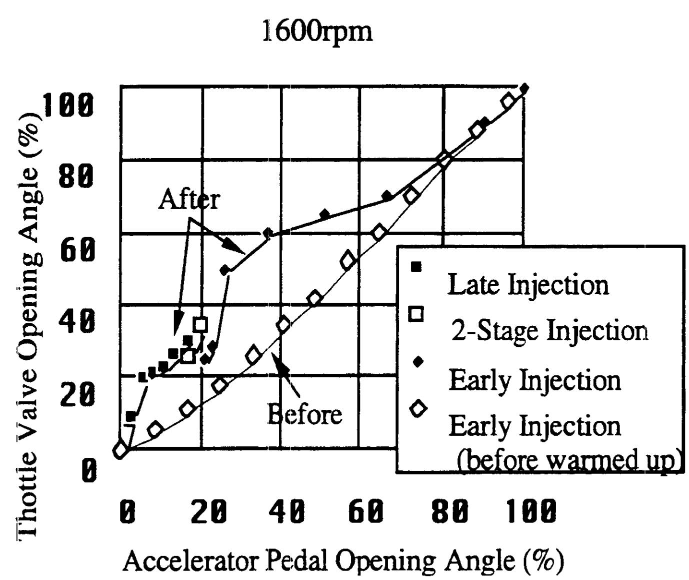


Fig.18 Throttle opening characteristics for before and after warm-up

cally controlled throttle system was employed for the new DI engine. The throttle valve is driven by a DC motor and mechanically separate from the accelerator pedal.

Fig. 18 shows the throttle opening characteristics of the new DI engine, for before and after the warmed-up condition at 1600 rpm. In the former case, the engine is driven with homogeneous mixture throughout, and the operation is similar to conventional engines. In the latter case (after warm-up), operation is varied from stratified through homogeneous mixture. As shown in the figure, during stratified mixture (late injection) and the lean burn (early injection) operations, the throttle opening requirement is larger than the before warm-up case. It also shows non-continuous characteristics at the transition from late injection to early injection, via two-stage injection. These characteristics could be realized only by the electronically controlled throttle system.

EMISSIONS AND FUEL ECONOMY PERFORMANCE

The exhaust emissions and fuel economy performance in the Japanese 10-15 mode cycle were investigated (Table 2). These results were obtained from a vehicle with a 4-speed transmission and 1250 kg (2625 lbs) equivalent inertia weight. Compared to the production vehicle with a conventional 2.0 ℓ engine, fuel economy is improved by 35%, of which 22% is obtained by stratified lean operation and the rest by such things as refinement in lock-up control management in the automatic transmission.

The raw NOx emission (without EGR and NOx catalyst) is up to 1.85g/km in the Japanese 10-15 mode. With EGR control, NOx is reduced by 67% to 0.60g/km, and then reduced to 0.10g/km with a stabilized NOx catalyst. With the NOx storage-reduction catalyst, intermittent rich mixture supply control inevitably causes 2% of fuel efficiency loss, but this is acceptable considering NOx reduction performance.

Both HC and CO emissions were reduced successfully by the oxidization effect of the conventional three way catalyst.

SUMMARY

1. A new DI gasoline engine with stratified ultra-lean mixture operation realized 22% fuel economy improvement, featuring new technologies such as involute shape concave piston, swirl intake ports and high pressure fuel injection system.

2. Smoke generation was avoided over all engine operation areas by employing three types of injection strategies.

3. A seamless output torque transition was achieved with an electronic throttle control system.

4. Exhaust emissions satisfied Japanese standards with EGR, NOx storage-reduction catalyst and closed-coupled three way catalyst.

ACKNOWLEDGMENT

We wish to express our deepest appreciation to Toyota Central Research & Development Laboratories, Inc., Nippon Soken. Inc. and all the other companies who have helped us in developing this new DI gasoline engine.

Table 2 Emissions and fuel economy (Japan 10-15 mode cycle)

	FUEL ECONOMY (km/ ℓ)	HC (g/km)	CO (g/km)	NOx (g/km)	Test Conditions	
					EGR	Catalysts
Conventional Engine	13.0	-	-	-	—	—
DI Engine As Developed	17.5	0.10	0.05	0.10	○	○
DI Engine With EGR, No Catalysts	17.8	2.75	3.56	0.60	○	—
DI Engine Raw NOx Emission	17.8	-	-	1.85	—	—
Emission Standards	-	0.25	2.10	0.25	—	—

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