SAE TECHNICAL PAPER SERIES

2000-01-0531

Application of a New Combustion Concept to Direct Injection Gasoline Engine

Mutsumi Kanda, Toyokazu Baika, Senji Kato and Minoru Iwamuro
Toyota Motor Corp.

Makoto Koike and Akinori Saito
Toyota Central R&D Labs.Inc.

Reprinted From: Direct Injection SI Engine Technology 2000 (SP–1499)

The Engineering Society For Advancing Mobility Land Sea Air and Space
INTERNATIONAL

SAE 2000 World Congress
Detroit, Michigan
March 6–9, 2000

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

2000-01-0531

Application of a New Combustion Concept to Direct Injection Gasoline Engine

Mutsumi Kanda, Toyokazu Baika, Senji Kato and Minoru Iwamuro
Toyota Motor Corp.

Makoto Koike and Akinori Saito
Toyota Central R&D Labs.Inc.

ABSTRACT

A direct injection (DI) gasoline engine having a new stratified charge combustion system has been developed. This new combustion process (NCP) was achieved by a fan-shaped fuel spray and a combustion chamber with a shell-shaped cavity in the piston. Compared with the current Toyota D-4 engine, wider engine operating area with stratified combustion and higher output performance were obtained without a swirl control valve (SCV) and a helical port. This report presents the results of combustion analyses to optimize fuel spray characteristics and piston cavity shapes. Two factors were found to be important for achieving stable stratified combustion.

The first is to create a ball-shaped uniform mixture cloud in the vicinity of the spark plug. The optimum ball-shaped mixture cloud is produced with a fuel spray having early breakup characteristics and uniform distribution, and a suitable side wall shape in the piston cavity to avoid the dispersion of the mixture.

The second factor is to reduce the over-lean area in the piston cavity. A compact shell-shaped cavity was designed for this purpose. The resulting flame propagation improves combustion stability.

The effect of tumble motion was also investigated. The best combustion characteristics were obtained at weak tumble motion condition. Measurement results of in-cylinder flow by LDV showed that the fan-shaped fuel spray produces sufficient turbulence strength without extra intake air flow systems.

The application of the NCP to an actual 3L in-line 6 DI gasoline engine showed that in addition to satisfying Japanese regulations which start in from 2000, a fuel economy gain of more than 20% was obtained.

INTRODUCTION

Increasing the fuel economy of automotive engines is very important for saving energy and improving the global environment. DI gasoline engines which are able to achieve both better fuel economy and output power simultaneously, have been considered for many years as a possible solution for these problems [1-3]. MITSUBISHI was the first to introduce gasoline DI engines in the market in1996, and Toyota launched the D-4 engine later in the same year [4]. The main features of the D-4 stratified charge combustion system are:

1. Piston with involute shaped concave combustion chamber;
2. High pressure swirl fuel injector;
3. Intake system with a helical port and a swirl control valve (SCV).

This combustion system achieves a wide range of stratified combustion, but the output power is partially deteriorated by the helical port at high speed conditions. We have been conducting research and development of a new combustion system jointly with Toyota Central R&D Labs,Inc. to improve the previous system. This joint R&D resulted in a new combustion process (NCP), which realizes both wider range of stratified combustion and excellent homogeneous combustion without an extra intake air flow controlling system. This paper discusses the required characteristics of the fuel spray and piston cavity shapes that are the main elements of the NCP, and also presents the performance characteristics of an actual engine in which the NCP was utilized.

NCP AND TEST ENGINE

Figure 1 shows a schematic of the NCP and Table 1 shows the main specifications of the test engine. The NCP has the following two features:

1. Piston with shell-shaped cavity to control mixture formation and flame propagation;
2. High pressure fan-shaped fuel injector with wide spray dispersion and moderate spray penetration to control mixture formation;

The intake system uses a straight intake port, similar to that of a conventional engine. To obtain stratified combustion, fuel is injected in the cylinder during the compression stroke, and a stratified mixture cloud is formed in the combustion chamber by means of both the piston cavity shape and the fuel spray with the characteristics of wide-angle and fine atomization. To obtain homogeneous combustion, fuel is injected in the cylinder during the intake stroke, and a homogeneous mixture cloud is formed in the combustion chamber by means of the fuel spray characteristics, i.e. wide-angle, fine atomization and moderate penetration.

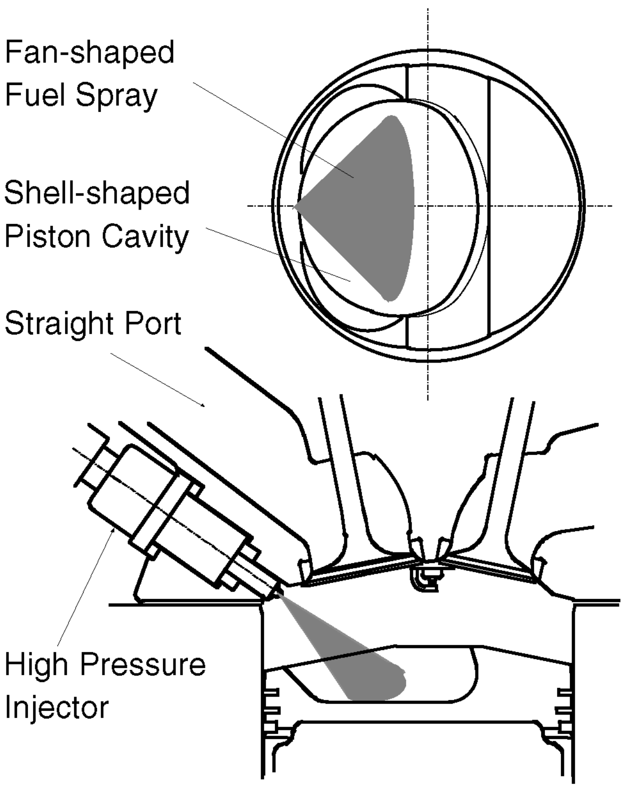


Figure 1. Fuel spray and piston cavity configuration

Table 1. Engine specification

Engine Type	4-stroke,in-line,4-cylinder DOHC 4-valve
Displacement	1,998cc
Bore,Stroke	86mm,86mm
Compression ratio	10.3
Fuel pressure	~ 12MPa

FACTORS OF NCP AT STRATIFIED COMBUSTION

Figure 2 shows photographs of the fan-shaped fuel spray under ambient atmosphere pressure of 0.6 MPa, taken 2 ms. after the start of injection. It has the fuel spray angle of about 50 degrees in a front of view and of about 20 degrees in a side view. Table 2 shows a comparison of the Sauter Mean Diameter (SMD) of the fan-shaped spray and the swirl fuel spray which is used for the conventional DI gasoline engine (D-4) of Toyota. The droplet diameter of the fan-shaped fuel spray is approximately 20mm, which smaller than the swirl spray. Figure 3 shows the relation between penetration distance of fuel spray and delayed time from the start of injection. At 2ms. after the start of injection, the fan-shaped fuel spray has a stronger spray penetration of approximately 70mm, compared to approximately 60mm for the swirl fuel spray. The breakup points of both spray types shown in Figure 3 occur at less than 1ms. Here, the breakup point is defined to be where the injected fuel changes behavior from liquid jet flow to the flow of fine size droplets, and the speed of initial fuel spray begins to decrease.

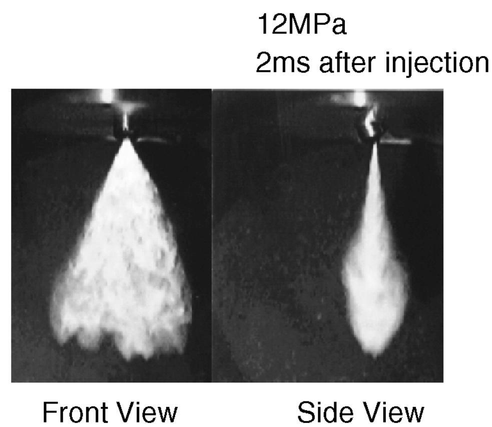


Figure 2. Fuel spray shape

Table 2. Sauter Mean Diameter(0.6MPa)

	Fan Spray	Swirl Spray
SMD	20 µm	23 µm

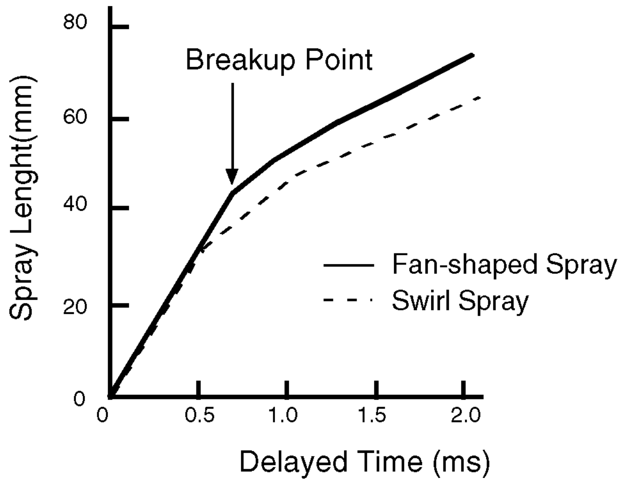


Figure 3. Spray penetration

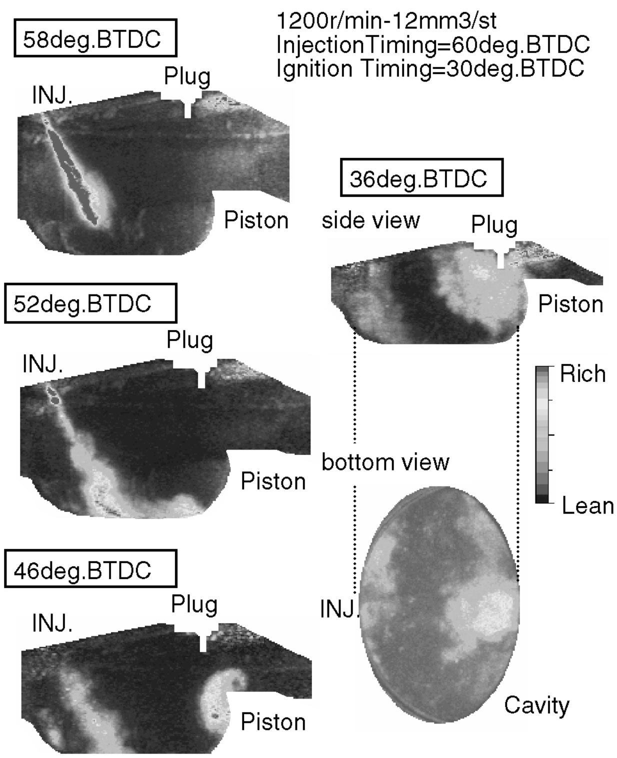


Figure 4. Fuel spray motion and mixture distribution (LIF measurements)

Figure 4 shows the stratified mixture formation process in the cylinder as visualized by the LIF (Laser Induced Fluorescence) technique. Fuel that was injected toward the piston cavity during the compression stroke impinges on the cavity lower surface and then moves toward the spark plug side along the lower surface and the opposite wall. A ball-shaped mixture cloud is then formed near the spark plug. To analyze the mixture formation process, the in-cylinder gas motion was observed by high speed photography with micro-balloons as tracers, and flow vectors were obtained from these images by PIV analysis. Figure 5 shows the gas motion induced by fuel that was injected into the cylinder. Vectors of gas flow are directed toward the spark plug along the surface of the shell-shaped piston cavity, and develop into a turning flow in the vertical direction, resulting in a ball-shaped mixture cloud in the vicinity of the spark plug.

In-cylinder analytical results also revealed the following three characteristic phenomena:

1. The breakup point of the injected fuel spray occurs just before it impinges on the lower surface of the piston cavity (Fig. 6);
2. When the fuel spray impinges on the lower surface of the piston cavity, a part of the fuel spray runs back toward the injector side to form a dilute mixture cloud (Fig. 4);
3. The ball-shaped mixture cloud formed in the vicinity of the spark plug diffuses when it is pushed outward by flame propagation. The flame grows as it engulfs the mixture cloud near the injector. As a result, a flammable mixture cloud is always able to exist in front of the flame (contours denoted in Fig. 7 show the flame front).

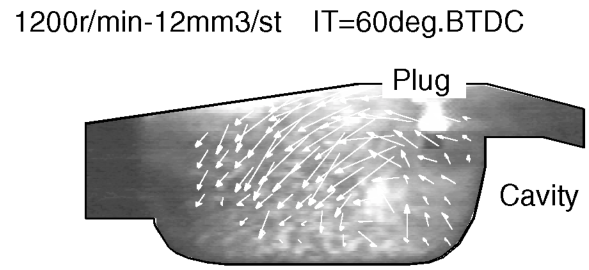


Figure 5. In-cylinder flow pattern

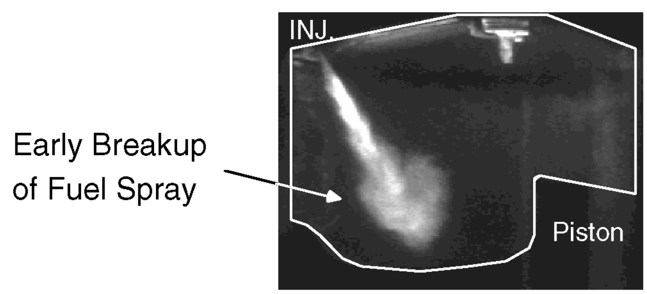


Figure 6. In-cylinder spray photograph of early breakup injector

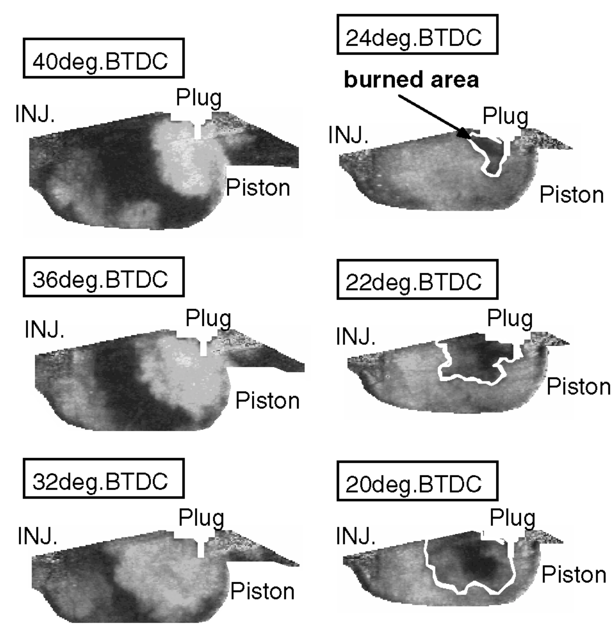


Figure 7. Mixture motion and flame propagation images of early breakup injector (LIF measurements)

Figure 8 indicates equivalence ratios near the spark plug calculated from measurements of HC concentration by a fast response gas sampling system (Cambustion). The calibration was made from HC concentration at homogeneous combustion. The equivalence ratio changed little as sampling timing was varied at a constant injection timing. These results indicate that the NCP achieves a stable mixture formation.

Figure 9 shows measurement results of flow velocity at the spark plug by LDV. The measurements were performed at a motoring condition through a quartz window fixed at a spark plug hole. A positive direction was defined as moving from intake valve side to exhaust valve side. The results with fuel injection shows a large negative peak of flow velocity at about 60 deg. ATDC, which can be explained by a turning flow generated by the fan-shaped fuel spray when it follows the contour of the shell-shaped piston cavity. Table 3 shows the mean turbulent intensity averaged between 30 deg. BTDC and TDC, compared with that of a lean burn engine (7A-FE) of Toyota having a helical port with SCV [5,6]. The mean turbulent intensity of the NCP with fuel injection indicated a higher value than the lean burn engine with SCV closed. From this, it is evident that the NCP has an effective turbulent intensity for combustion acceleration in stratified combustion.

Next, the fuel spray characteristics and different piston cavity shapes were examined experimentally to observe their effects on stratified combustion and torque fluctuations.

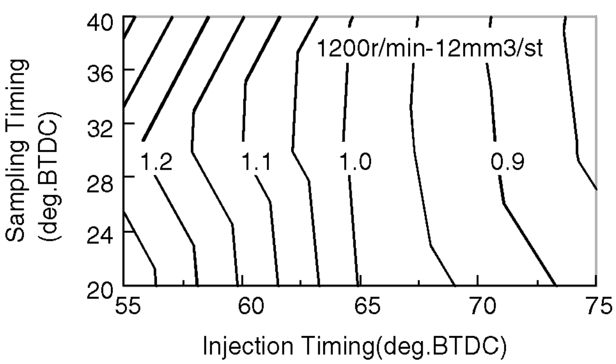


Figure 8. Equivalence ratio nearby spark plug (Fast response gas sampling)

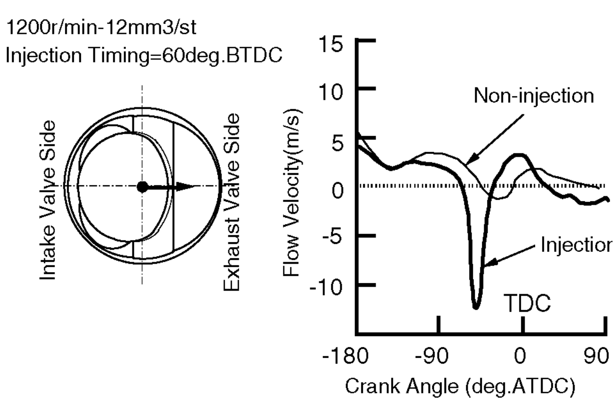
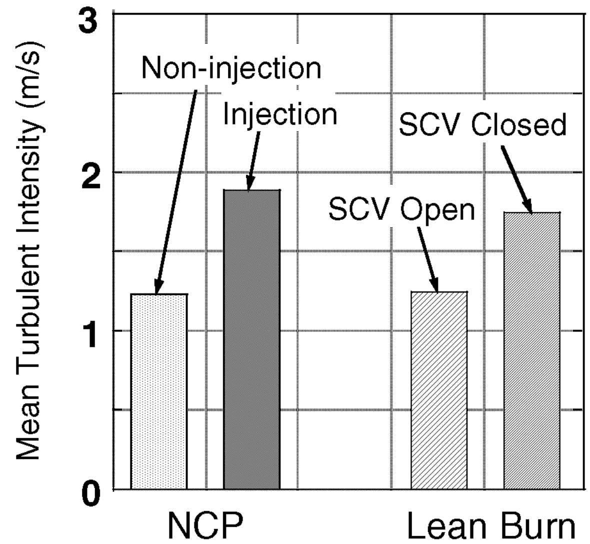


Figure 9. Flow velocity

Table 3. Turbulent intensity



EFFECTS OF FUEL SPRAY CHARACTERISTICS – An injector with late breakup was manufactured, and its effects on mixture formation and combustion were investigated. Figure 10 shows a photograph of fuel spray at the same timing as Fig 6, but it hardly discerns the breakup. Figure 11 shows mixture cloud behavior in the piston cavity and flame propagation process using this fuel spray. In the case of the fuel spray with late breakup, evaporation was slow after impingement on the cavity lower surface, and dispersion was weak, such that the mixture cloud did not grow very much. This resulted in a one-sided shape at the cavity wall of spark plug side instead of a bowl shape, and a comparatively dense rich region was formed in the mixture cloud. Thus, diffusion of the mixture cloud was slow and the mixture cloud quantity which is pushed outward by flame propagation decreased. As a result, an over-lean area was formed between the mixture cloud of the injector side and the spark plug side, and flame propagation was decelerated at over-lean area. Figure 12 and Table 4 shows pressure indicator diagrams of the two different types of fuel spray breakup. The fuel spray with late breakup showed a low peak of heat release rate and a long combustion period of the last half. Moreover an indicated mean effective pressure (IMEP) was lower and its fluctuation rate (σ/IMEP) indicated a larger value. From these results, the breakup characteristics of fuel spray were found to accomplish an important role for the mixture formation and the flame propagation of the NCP.

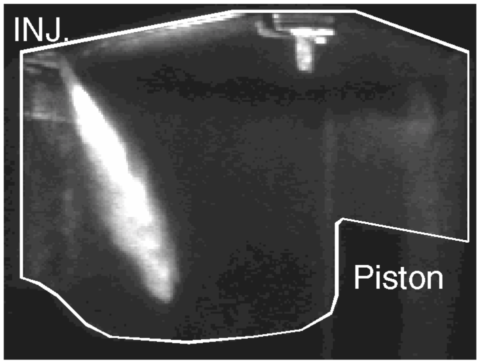


Figure 10. In-cylinder spray photograph of late breakup injector

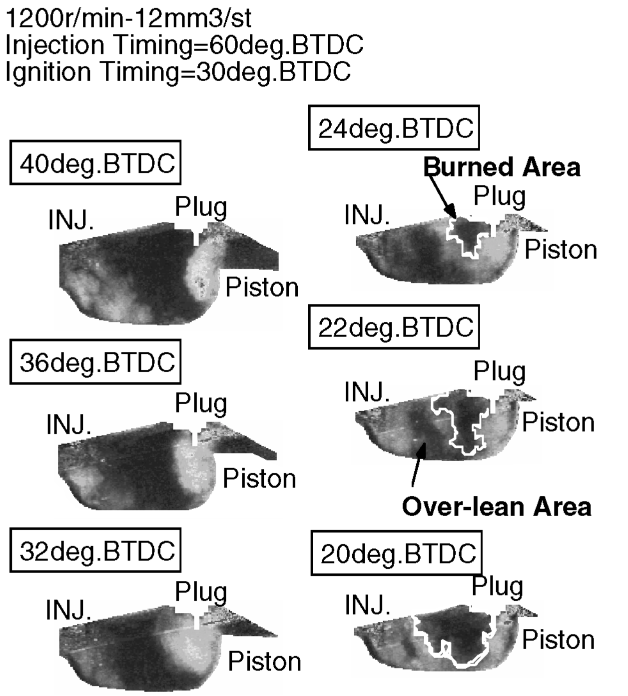


Figure 11. Mixture motion and flame propagation images of late breakup injector (LIF measurements)

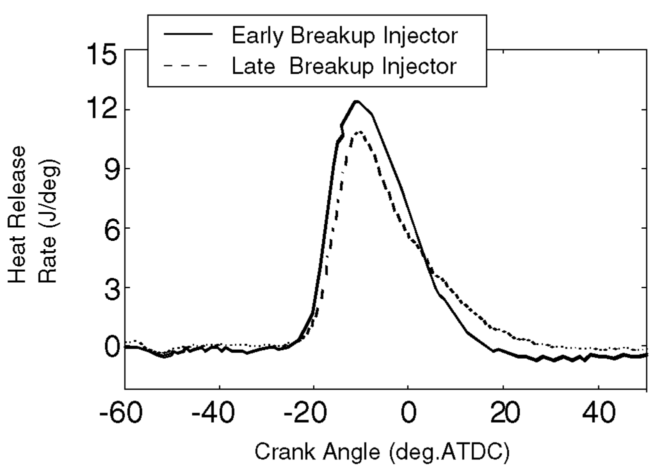


Figure 12. Effects of injectors on heat release rate

Table 4. Effects of injectors on IMEP and σ/IMEP

Injector	IMEP(MPa)	σ/IMEP(%)
Early Breakup	0.264	2.34
Late Breakup	0.241	4.08

EFFECTS OF PISTON CAVITY SHAPES – The role of the piston cavity shape in forming the mixture -cloud was demonstrated in the previous section (FACTORS OF NCP AT STRATIFIED COMBUSTION). Here, we describe another role of the cavity in improving fluctuation rate of IMEP. Figure 13 shows the flame propagation process in a cavity (Cavity A) which is comparatively wider (numeric values in the figure show the crank angle after spark ignition). The flame propagation in the cavity was visualized by high speed photography through a special quartz piston from the bottom view of the cylinder. The flame propagation progressed rapidly toward the injector side from the spark plug. On the other hand, a portion of the flame contours at its orthogonal direction became very narrow after 30deg after spark ignition, indicating that the propagation is very slow. It is thought that the acceleration of flame propagation in this area is related to shortening of the last half of the combustion period, and it was important for lowering torque fluctuations. For this purpose, a more detailed study of cavity shapes was carried out. After much trial and error, a comparatively compact cavity shape (cavity B) proved to be effective. Figure 14 shows the outline shape of the cavity and flame propagation process. In the compact cavity, the distance to the side wall to which the flame propagates was reduced and the curvature of the side wall was also optimized for mixture formation. Besides, in order to keep the compression ratio same, a squash clearance of the exhaust side was varied. As can been seen in Figures 13 and 14, flame propagation velocity on orthogonal direction was about the same as that toward the injector side. As a result, flame propagation in the cavity B finished earlier than the cavity A. Figure 15 and Table 5 shows results of pressure indicator analysis in both cavities which were measured at best spark timings. It was shown that the compact cavity (cavity B) accelerated the heat release rate of the last half and shortened the combustion period, and thereby the IMEP and its fluctuation rate were improved. From these results, flame propagation improvement in the orthogonal direction in the cavity was considered to have an effect on the IMEP and its fluctuation rate improvements.

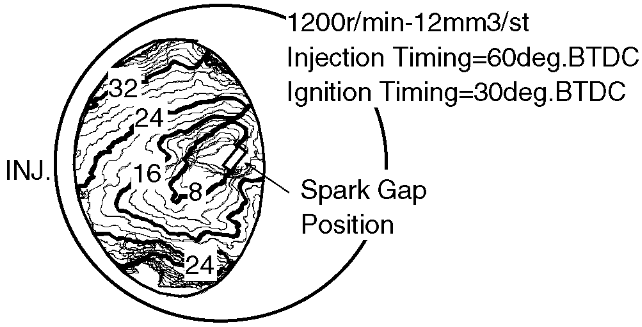


Figure 13. Flame propagation contour of cavity A

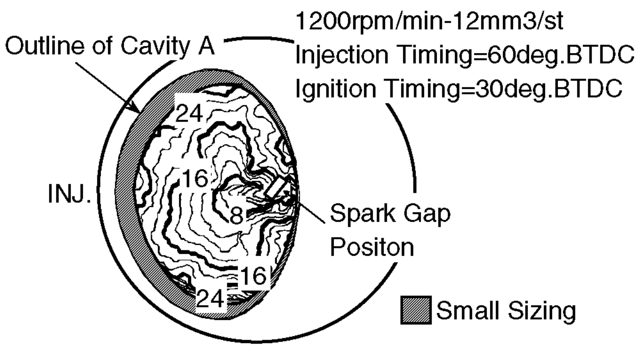


Figure 14. Flame propagation contour of cavity B

EFFECTS OF AIR FLOW – We investigated the effects of tumble flow in order to confirm whether the NCP was achieved stratified combustion by the fuel spray and the piston cavity shape without an extra charge motion. The results are shown in Figure 16. The tumble ratios in the figure show values measured by an impulse meter in continuous flow. The various tumble ratios were produced by varying the shape of the intake port. A weak tumble ratio correlated with low fuel consumption, HC emission and torque fluctuation rate. Performance deterioration at a stronger tumble ratio is due to the strong tumble flow persisting until the last half of the compression stroke, which disperses the mixture cloud. This result indicated that stable stratified combustion could be obtained with a tumble ratio 0.2 using a conventional straight port.

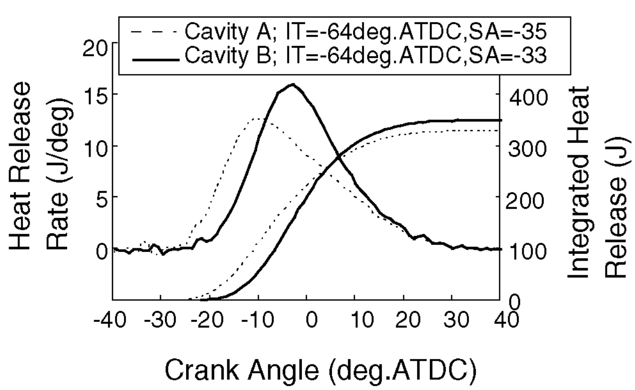


Figure 15. Effects of cavity shapes on heat release

Table 5. Effects of cavity shapes on IMEP and σ/IMEP

Cavity shape	IMEP(MPa)	σ/IMEP(%)
A	0.308	2.99
B	0.335	2.17

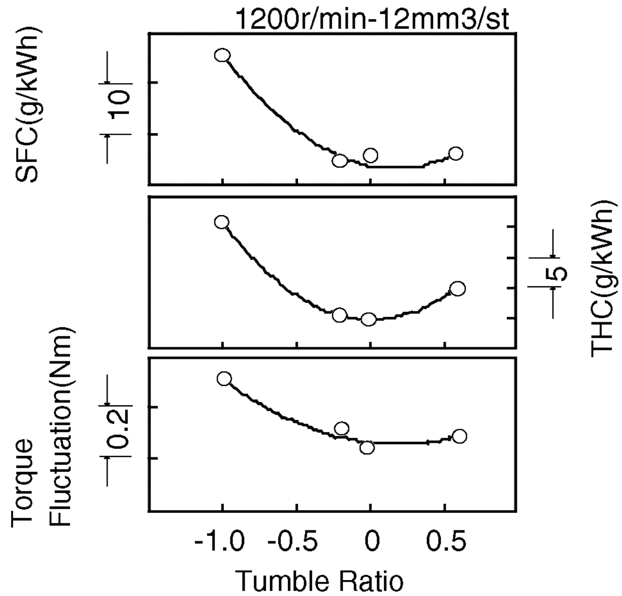


Figure 16. Effects of tumble ratio

COMPARISON OF STRATIFIED COMBUSTION AREA – Figure 17 shows a comparison of the stratified combustion operation areas of the NCP and the conventional DI gasoline engine of Toyota. The shaded area shows the points at which NOx emissions and torque fluctuation rate are kept below a certain threshold value. The NCP engine realized a wider range of stratified combustion not only at higher load but also higher rpm, compared with the conventional DI gasoline engine. The fuel spray has excellent distribution characteristics making it possible to inhibit over-rich mixture formation, even though injection quantity increases at high load condition. The fuel spray has comparatively high penetration and is able to form a certain mixture formation, even if the gas flow in the cylinder increases in high rpm areas. Therefore, the NCP resulted in an expanded stable stratified combustion area.

PROCESS OF HOMOGENEOUS COMBUSTION

Figure 18 shows the mixture formation process during intake stroke injection (200deg.BTDC). The optical engine was designed for compression stroke observation, so only half of the stroke can be seen. However, in-cylinder analytical results of this condition indicate the following phenomena:

1. The injected spray shows earlier breakup even under atmospheric pressure;
2. The injected fuel induces a gas motion in the cylinder;
3. The fuel impinged on the piston surface rolls up and diffuses in cylinder;
4. Near TDC, a uniform mixture cloud is formed. Hereby, it is indicated that the NCP realizes an excellent homogeneous combustion.

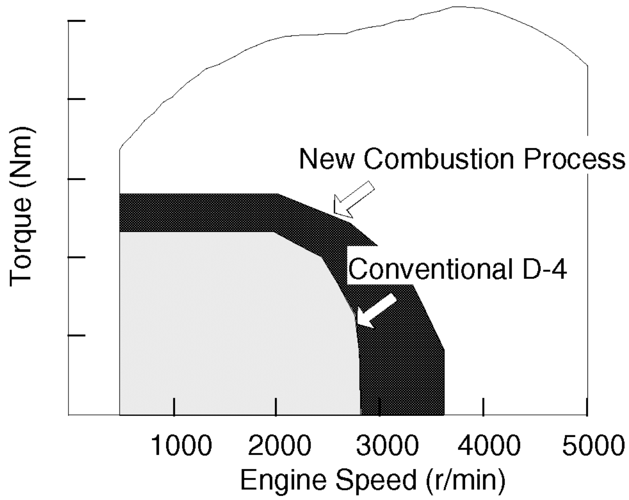


Figure 17. Comparison of stratified combustion area

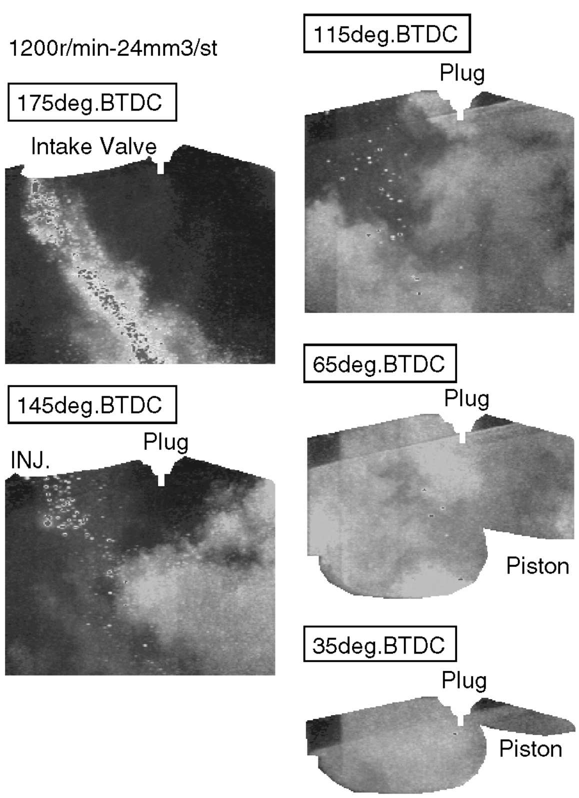


Figure 18. In-cylinder mixture distribution a intake stroke injector (LIF measurements)

RESULTS OF A FULL LOAD PERFORMANCE – Figure 19 shows results of full load performance of the NCP, compared with the conventional DI gasoline engine of Toyota. As can be seen, the NCP accomplished higher torque performance in almost all areas. The NCP is able to form a uniform mixture cloud in the cylinder during intake stroke injection. At this condition, the fuel spray has excellent atomization characteristics. It makes charging efficiency higher by the effect of latent vaporization heat. Therefore torque at the low speed area was improved. Also the straight intake port of NCP is able to increase air flow rate at the high speed area compared with the conventional DI gasoline engine with helical port. Therefore torque at high speed was also improved.

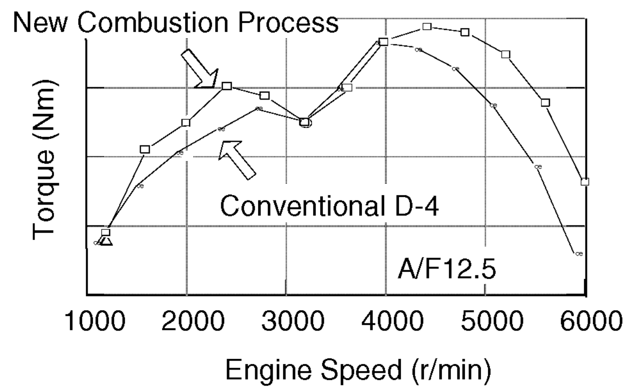


Figure 19. Torque improvements at WOT conditions

APPLICATION TO THE NEW DI GASOLINE ENGINE

Figure 20 shows a photograph of a new 3L in-line 6 DI gasoline engine to which the NCP was applied. Figure 21 shows a schematic diagram of DI system. The content of the NCP system has been refined; however, the basic composition is similar to the conventional DI system. The air flow control valves in the figure were adopted firstly for torque improvement from low to middle speed area at full load conditions and secondly for HC emission improvement at low temperature conditions. The valves are closed at above-mentioned operating conditions, but they are opened at the other area conditions (include at stratified combustion area).

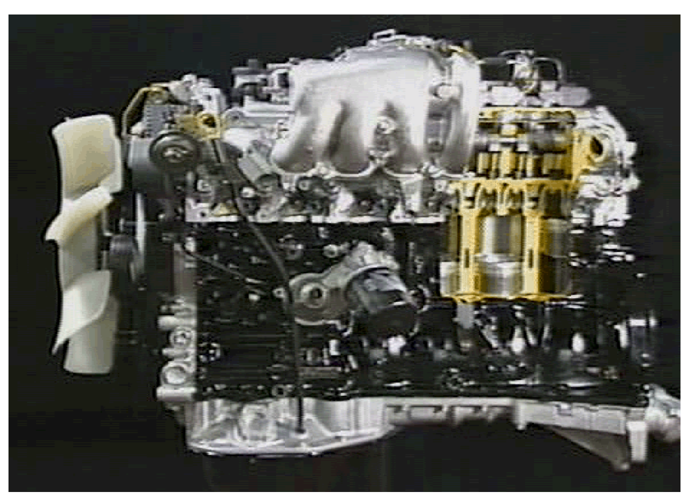


Figure 20. A New DI gasoline engine

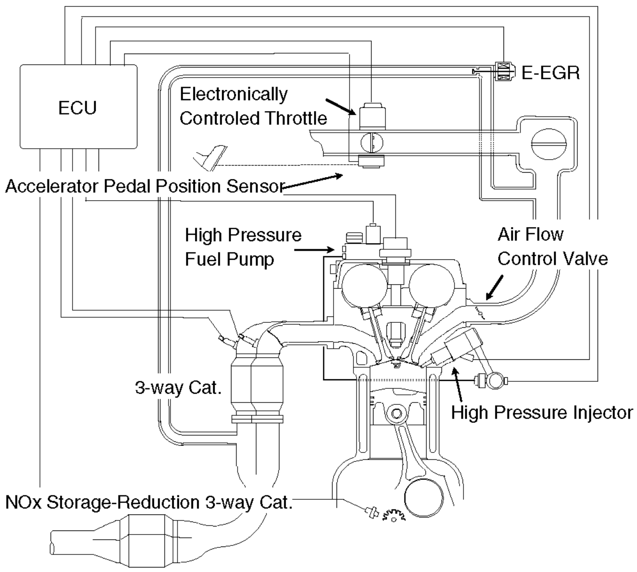


Figure 21. Schematic diagram of DI system

EMISSIONS AND FUEL ECONOMY – Table 6 shows the exhaust emissions and fuel economy of the new engine tested with the 10-15 mode cycle, compared to the Japanese new regulation which start in 2000. These results were obtained from a vehicle with a 5 speed automatic transmission and 1750 kg (3675 lbs) equivalent inertia weight. Compared to the production vehicle with a conventional 3L engine, in additional to satisfying the emissions regulation, a fuel economy gain of more than 20% was obtained.

Table 6. Emissions and fuel economy (Japan 10-15 mode cycle)

	Fuel Economy (Km/ ℓ)	HC (g/km)	CO (g/km)	NOx (g/km)
Conventional Engine	9.4	—	—	—
New DI Engine	11.4	0.054	0.609	0.054
Emission Standards	—	0.08	0.67	0.08

CONCLUSION

The analysis of in-cylinder phenomena of the NCP revealed that the following points are important for realization of stable stratified combustion:

1. A flammable mixture cloud of a stable ball-shape with high turbulent intensity should be formed in the vicinity of the spark plug.
2. In addition to optimizing the piston cavity shape, an injector with early breakup is required.
3. The side wall shape of the cavity is important in controlling torque fluctuation by accelerating combustion.

The NCP has an optimized combustion system which demonstrates the following performance in comparison with the conventional DI gasoline engine:

1. The stability range of stratified combustion was enlarged.
2. The full load torque improved at most speeds.

The NCP was applied to an actual 3L in-line 6 DI gasoline engine, and the exhaust emissions and fuel economy performance in the Japanese 10-15 mode cycle were investigated. The results show that in addition to satisfying Japanese regulation which starts in 2000, a fuel economy more than 20% was obtained.

ACKNOWLEDGMENTS

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

REFERENCES

1. Alperstein, M., Schafer, G., Villforth, F., "Texaco's Stratified Charge Engine_Multifuel, Efficient, Clean and Practical," SAE 740563
2. Scussel, A., Simko, A.,Wade,W.,"The Ford PROCO Engine Update," SAE 780699
3. Schäpertöns, H., Emmenthal, K.-D.,Grade, H.-J., Oppermann, W., "VW's Gasoline Direct Injection (GDI) Reserch Engine," SAE 910054
4. Harada, J., Tomita, T., Mizuno, H., Mashiki, Z., Ito, Y., "Development of Direct Injection Gasoline Engine", SAE 970540
5. Matsusita,S., et al., "Effect of Helical Port with Swirl Control Valve on Combustion and Performance of S.I. Engine," SAE 850046
6. Nakanishi, K., et al., "Development of a New Intake System for a 4--valve Lean Burn Engine," FISITA No.925020, 1992