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ABSTRACT

A direct injection spark ignition (DISI) gasoline engine with a new stratified charge combustion concept has been launched on the Japanese domestic market. This new concept consists of two components. First, a thin fan-shaped spray from a slit nozzle enables wide spray dispersion, moderate spray penetration and a fine atomization. Second, a shell-shaped piston cavity allows better mixture formation, however avoiding distinct charge motions (such as tumble or swirl). Simple intake port geometry increases the full load performance. The combustion concept, at the same time allows stratified charge to be used at higher load and at higher engine speeds and improves the homogeneous charge combustion. A new 3L in-line 6 gasoline engine with this combustion concept showed 20% better fuel economy than a 3L port fuel injection (PFI) engine (λ=1 feed back system) under the Japanese 10-15 mode.

INTRODUCTION

The importance of improved fuel economy increases along with increased concerns about the enhanced green house effect, suspected to be partly caused by our emissions of carbon dioxide. Several manufacturers [1,2,3] are therefore introducing high performance DISI gasoline engines that enable good fuel economy. DISI gasoline engines utilise the in-cylinder charge motion to guide the mixture to the spark plug area. However, generated air motion sometimes creates lower volumetric efficiency, higher cooling and pumping loss, or becomes sensitive to the cycle-by-cycle variation of the in-cylinder charge motion. We have therefore developed a new combustion concept, which does not depend on air charge motion [4,5]. This paper describes the influence of nozzle specifications on spray characteristics (based on practical experiments as well as CFD calculations), and on mixture formation in the new combustion concept, and also presents the engine performance of the new DISI gasoline engine compared with the first generation TOYOTA DISI gasoline engine.

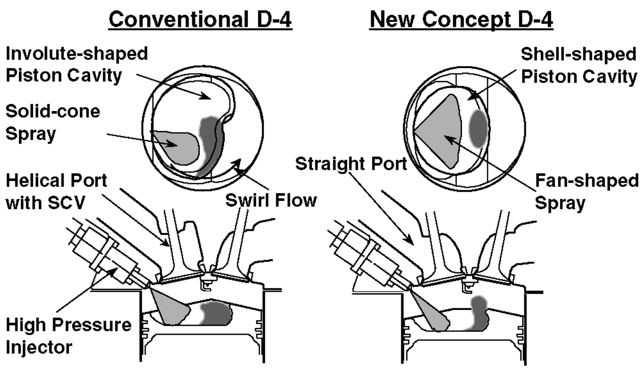
REQUIRED CHARACTERISTICS OF THE SPRAY

REQUIREMENTS OF THE COMBUSTION SYSTEM – Currently, in most combustion chamber configurations of the DISI gasoline engines the fuel injector and the spark plug are not installed close to each other and the spraying angle is adjusted in order not to hit the spark plug directly. For these combustion systems, swirl nozzle type fuel injectors are used. If a wider spray cone angle is selected, in order to achieve a higher dispersion, the spray penetration is reduced, and it becomes difficult to ensure a good mixture near the spark plug. So, to guide the mixture to the spark plug the in-cylinder charge motion serves a very important role. Our new combustion concept, adopting the straight intake port for higher output performance requires a new mixture preparation procedure, which does not depend on high velocity of the in-cylinder charge motion. In other words, preparation of the mixture in the area near to the spark plug comes from the moderate spray penetration caused by spray itself and by optimised piston top configuration. Therefore, in this combustion concept, spray characteristics (spray dispersion, spray penetration and fuel atomization) are very important factors for mixture formation. Figure 1 shows the fuel spray and piston cavity configuration of the new DISI gasoline engine (New concept D-4) compared with the first generation TOYOTA DISI gasoline engine (Conventional D-4) [1].

Summaries of spray requirements are as follows:

1. Moderate Penetration: Mixture preparation by shearing force of the spray and guide the mixture near to the ignition plug.

2. Wide Dispersion: Prevents too rich mixture and homogenization inside the mixture.
3. Thin Fan-shaped Spray: Increasing the shearing area with the air of the spray makes the air roll into the spray easier, and enlarge the stratified charge combustion area.
4. Fine Atomization: Promotes the mixture preparation.



preparation.

Figure 1. Combustion System Configuration

NOZZLE SPECIFICATIONS – The fuel injector of the current DISI gasoline engines is normally fitted with a swirl type nozzle. The spray shape of the swirl type nozzle is like a hollow cone or a solid cone spray, and generally speaking the wider the spray angle the hollower the cone becomes. However, the slit nozzle adopted in our new concept produces a thin fan-shaped spray. We studied three types of nozzles considering the requirement for the splay. Figure 2 shows the slit nozzle hole configuration. There is a sac downstream of the valve sheet, and the thin slit nozzle hole is shaped towards the outside of the sac wall. The slit nozzle is produced by fine electric discharge processing [6].

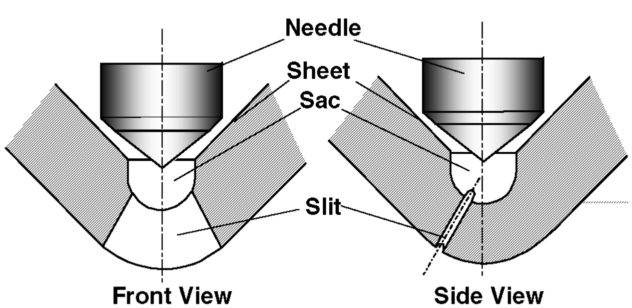


Figure 2. Slit Nozzle

Figure 3 shows photographs of two swirl nozzles and a slit nozzle spray captured 2ms after the start of injection. The hollow cone spray shows wide dispersion with lower penetration, whereas the solid cone spray shows narrow dispersion with higher penetration. Both of them show thick vertical dispersion. In case of the slit nozzle, the spray disperses wider in horizontal direction but thinner in vertical direction. Compared with the swirl nozzle the thin fan-shaped spray shows a longer spray length because of higher penetration. Figure 4 compares the spray length. The horizontal axis shows the time after start of injection. The spray length is longer from the thin fan-shaped spray, medium from the solid cone spray and shorter from the hollow cone spray. This result represents the penetration forces of each spray shapes.

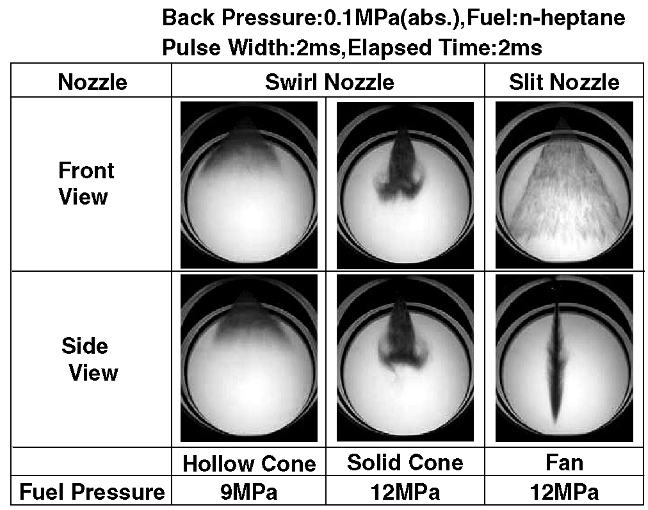


Figure 3. Spray Type

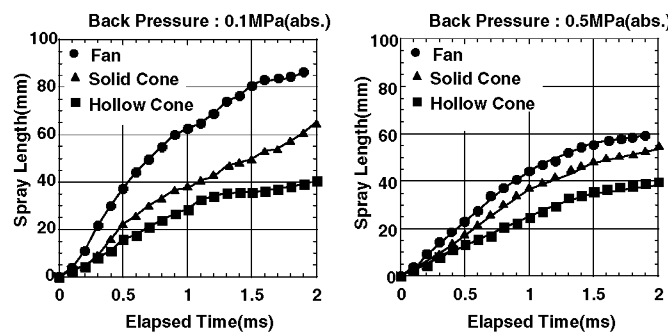


Figure 4. Spray Length

Figure 5 shows the cross-sectional fuel droplet size distribution of a swirl and a slit nozzle, measured by PDPA (Phase Doppler Particle Analyser) at 40mm downstream from the nozzle. (The swirl nozzle is the one used for the conventional D-4 engine.) The Sauter Mean Diameter (SMD) of the fan-shaped fuel spray is 20μm, which smaller than in the case of the swirl spray. As shown in this figure, the characteristics of the slit nozzle with its thin fan-shaped spray performance suit the new concept D-4 well.

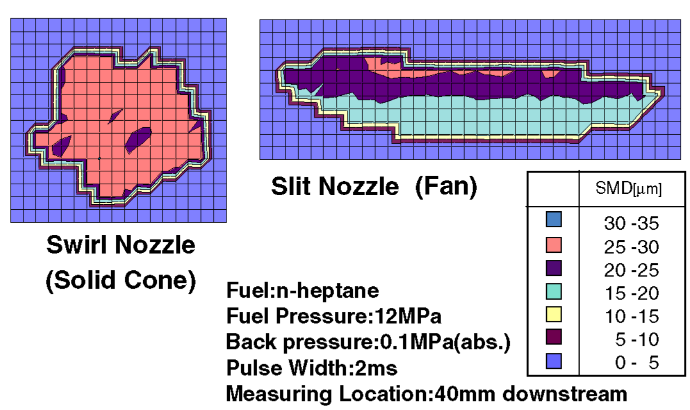


Figure 5. Droplet Size Distribution

SLIT NOZZLE HOLE SPECIFICATIONS

BASIC SPECIFICATIONS – Figure 6 shows nozzle specifications. A thin fan-shaped slit (thickness 0.1-0.2mm) is formed on the sac wall. The angle between the two sides of the fan shaped nozzle hole is θ_f, distance between the centre of the sac and the cross point of the extrapolated sides is B and the angle between the thin slit axis and injector centre axis is α.

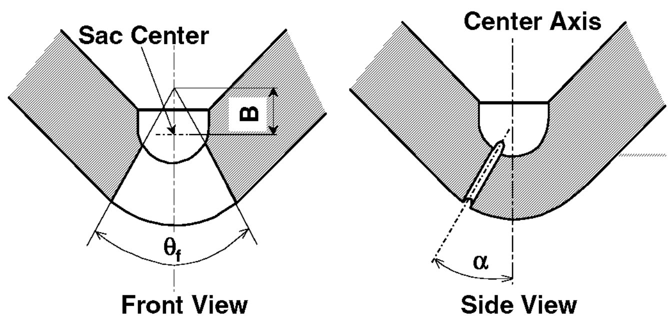


Figure 6. Slit Nozzle

Figure 7 displays the results of CFD calculations of the flow rate vectors when B is varied. Shorter B results in a higher flow rate at the centre of the spray with no flow along the side-wall. On the other hand, increased B results in increased flow rate of flow along the side-wall.

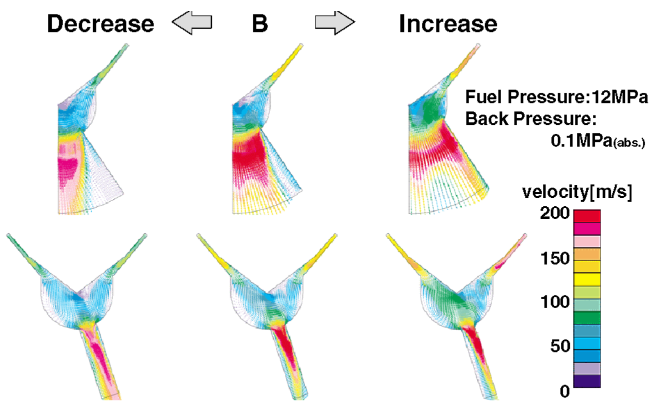


Figure 7. Effect of B on Flow

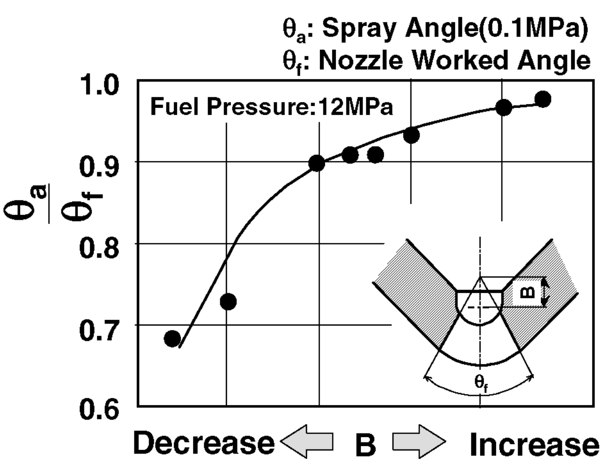


Figure 8. Effect of B on Spray Angle

Figure 8 shows the relationship between B and θ_a/θ_f, where θ_a is the spraying angle at a back-pressure of 0.1MPa. The bigger the vertical axis the smaller the difference between θ_a and θ_f becomes. Therefore, reducing B results in reduced θ_a/θ_f-ratios, whereas a longer B results in greater θ_a/θ_f-ratios. This phenomenon matches the calculated results shown in Figure 7. Note that, even with an extreme increase of B, θ_a cannot exceed θ_f. However, such an increase of B will affect the flux distribution of droplet volume, but generally it can be said that with a longer B, the smaller the sensitivity of B and θ_a becomes. Next, we studied the effect of B on the relative spray angle with back-pressure change. Figure 9 shows the relationship between B and θ_p/θ_a, where θ_p is the spraying angle at a back-pressure of 0.5MPa. When B is reduced we find that θ_p becomes smaller than θ_a. In other words, the higher back pressure the lower the spray angle. Generally speaking, increased B results in the θ_p/θ_a-ratio going towards 1, and also in reduced influence of B on θ_p/θ_a.

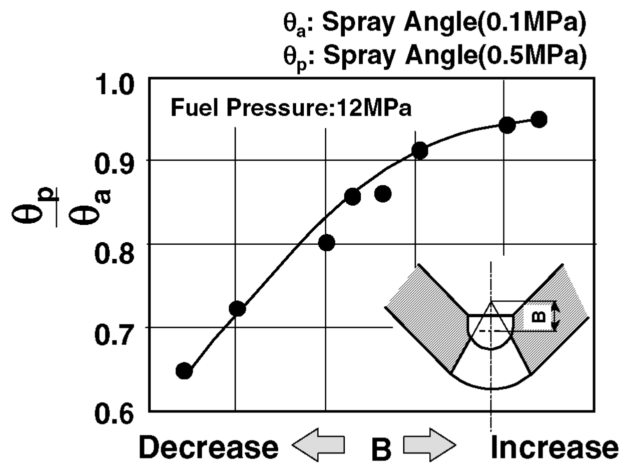


Figure 9. Effect of B on Spray Angle

Figure 10 shows spray shapes and droplets volume flux distribution. As with the flow rate, decreased B results in a higher volume flux at the centre of the spray (centre projected spray), and an increase of B results in a higher volume flux near the side wall (centre recessed spray), where the overall droplet size and spray penetration of the whole spray are the same.

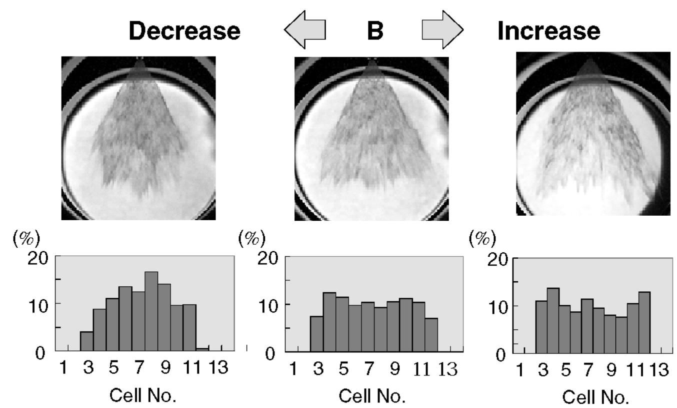


Figure 10. Spray Shape and Distribution

We can change the spray characteristics, such as volume flux distribution and relative spray angle variability (by back-pressure) simply by adjusting B.

SPECIFICATIONS APPLIED FOR ENGINE – Requirements for the Spray angle (θ) depend on the engine specifications (Cylinder bore diameter, Piston stroke, Piston cavity shape, etc). The injection angle was aligned towards the piston top from the fuel injector axis (due to the engine packaging requirement) and the direction of the injection was adjusted by the angle α as shown in Figure 6. Figure 11 shows the results of CFD calculations of flow rate vectors from the nozzle hole when θ_f is varied. If B is constant, the flow rate distributions are almost the same regardless of θ_f, so we can comply with various spray angles required by various bore diameters, without observing any change in the flow rate distribution. Figure 12 shows the results of CFD calculations of flow rate vectors from the nozzle hole when α is varied. The flow rate vectors are almost constant regardless of α. We can therefore comply with various engine loading angles by only adjusting α without changing the spray characteristics. We can therefore select sprays suitable for various engine requirements by adjusting B, θ_f and α.

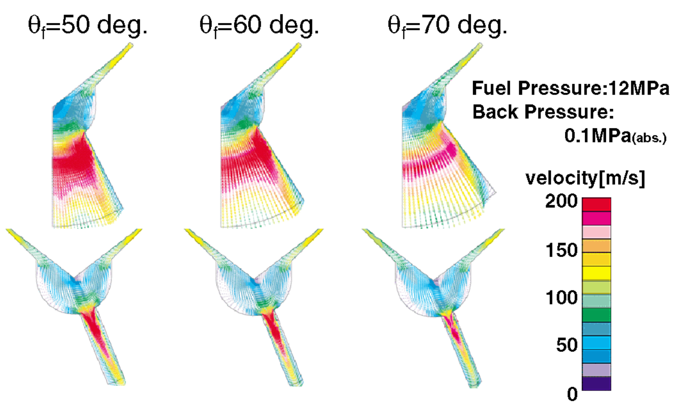


Figure 11. Effect of θ_f on Flow

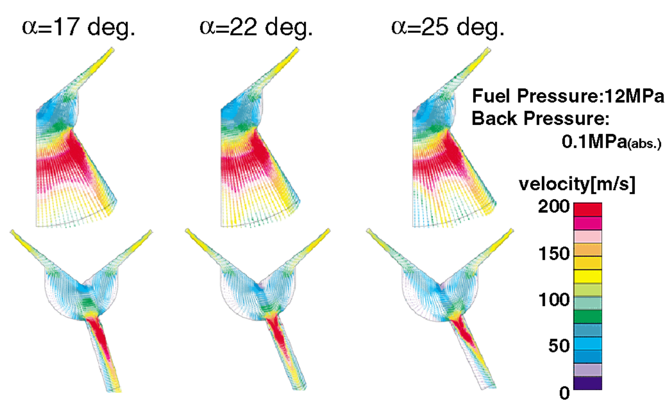


Figure 12. Effect of α on Flow

MIXTURE PREPARATION AND ENGINE PERFORMANCE

MIXTURE PREPARATION – Table 1 shows the main engine specifications used for the engine tests and CFD analysis. We studied the mixture formation with various spray configurations. Figure 13 shows spray shapes calculated with CFD analysis, utilizing Star CD software. With specified values of θ_p=56^o and α=23^o, three levels of both volume flux and velocity, and centre projection, even and centre recessed shapes of sprays were calculated.

Table 1. Test Engine Specifications

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**

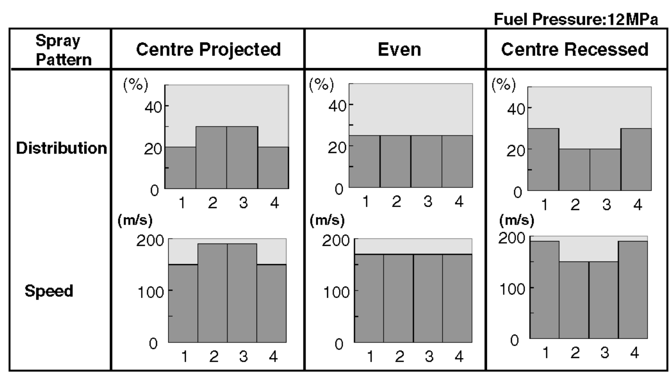


Figure 13. Spray pattern

Figure 14 shows the results of CFD calculations of the air fuel ratio (A/F) distribution. The even shaped spray enables a ball-shaped mixture close to the spark plug, forming a suitable mixture formation. While the centre projected spray forms a rich mixture in the vicinity of the spark plug, and the centre recessed spray forms a rich mixture on both sides of the spark plug.

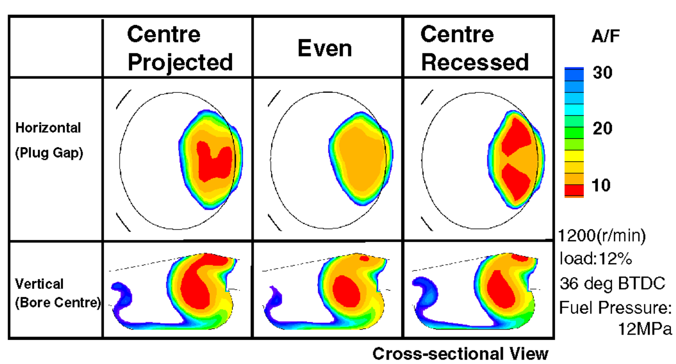


Figure 14. Mixture Formation

Figure 15 shows the stratified mixture formation process in the cylinder for the even shaped spray, which was visualized by LIF (Laser Induced Fluorescence) measurements. Fuel that was injected toward the piston cavity at the compression stroke moves toward the exhaust valve side along the lower surface, and reaches the opposite concave wall. The mixture is further transported toward the spark plug and forms a ball-shaped mixture cloud in the vicinity of the spark plug.

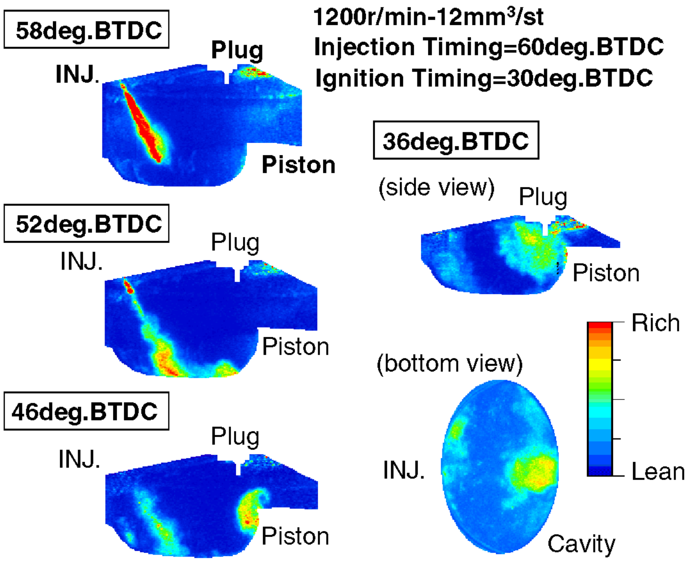


Figure 15. LIF Measurements of Mixture Formation Process

ENGINE PERFORMANCE – Table 2 shows the results of the engine performance evaluation with these three types of sprays. Torque fluctuation misfire, spark plug fouling, WOT torque, and WOT smoke were evaluated. The even shaped spray showed better performance compared with the centre projected and centre recessed sprays. The results of the stratified charge combustion match the results of the CFD calculations. Better WOT performance is due to the more homogeneous mixture.

Table 2. Engine Performance

+:Good -:Poor

Items \ Spray Pattern		Center Projected	Even	Center Recessed
Stratified	(Torque Fluctuation)	-	+	+
	(Miss Fire)	-	+	-
Homogeneous (WOT)	(Torque)	-	+	+
	(Smoke)	-	+	+

Figure 16 shows the stratified combustion operation areas of the new concept D-4 engine compared with the conventional D-4 engine. The shaded area shows the region where NOx emissions and torque fluctuation are kept below a certain level. The new concept D-4 engine achieved a wider range of stratified combustion not only at higher load but also at higher engine speed, compared with the conventional D-4 engine. Figure 17 shows the full load performance of the new concept D-4 engine, compared with the conventional D-4 engine. As can be seen, the new concept D-4 engine accomplished higher torque performance in almost all areas. The new concept D-4 system is able to form a uniform mixture cloud in the cylinder during intake stroke injection. In this case, the fuel spray has excellent atomization characteristics. Charging efficiency is increased and knock is improved by the effect of latent vaporization heat. Therefore torque at the low speed condition is improved. Also the straight intake port of the new combustion concept is able to increase air-flow rate at the high-speed condition, in comparison with the conventional D-4 engine with a helical port, and results in higher torque at high speed condition.

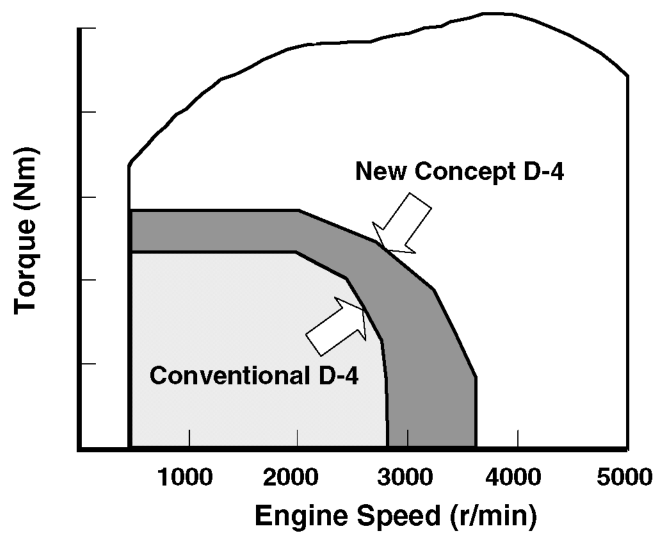


Figure 16. Improved Stratified Combustion Area with New Combustion Concept

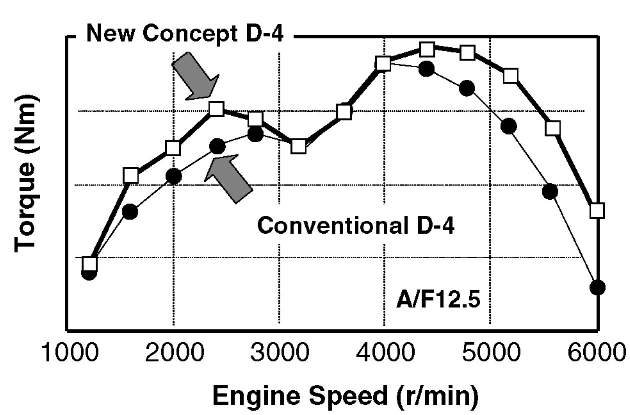


Figure 17. Full Load Performance

APPLICATION TO NEW 6 CYLINDER GASOLINE ENGINE

ENGINE SPECIFICATIONS – Figure 18 shows a photograph of a new 3L in-line 6 DISI gasoline engine to which the new combustion concept was applied and introduced into the Japanese market in October 1999. Table 3 shows the main specifications of the new DISI gasoline engine. Its specifications are similar to the basic PFI engine, but the cylinder head and the piston were newly redesigned to apply the new combustion concept.

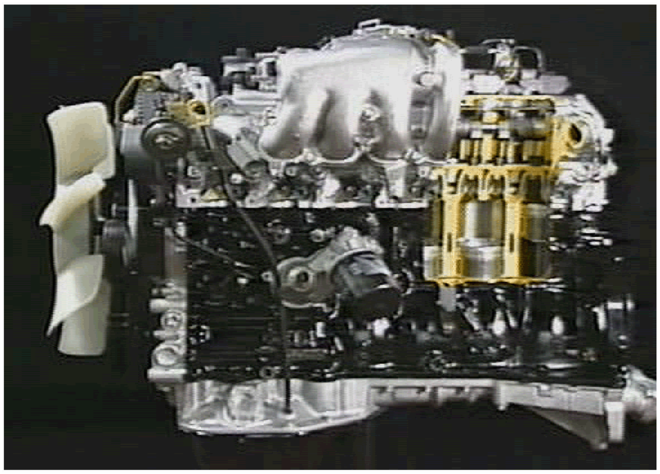


Figure 18. New 3L in-line 6 DISI Gasoline Engine

Table 3. Engine Specifications of New DISI Gasoline

Engine Type	4-stroke,in-line,6-cylinder DOHC 4-valve
Displacement	2,997cc
Bore,Stroke	86mm,86mm
Compression ratio	11.3
Fuel pressure	~12MPa

Table 4. Exhaust Emissions and Fuel Economy

	Fuel Economy (Km/L)	HC (g/km)	CO (g/km)	NOx (g/km)
New Model (DISI Engine)	11.4	0.054	0.609	0.054
Old Model (PFI Engine)	9.4	—	—	—
Japanese 10-15 Mode Emission Standards	—	0.08	0.67	0.08

EMISSION AND FUEL ECONOMY – Table 4 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 starts 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 previous vehicle with a conventional 3L PFI engine, in addition to satisfying the emissions regulation, a fuel economy gain of more than 20% has been obtained.

CONCLUSION

We analysed nozzle specifications and spray characteristics of fuel injector suitable for the new combustion concept and arrived to the following conclusions.

1. The thin fan-shaped spray with slit nozzle has the most suitable spray characteristics for the new combustion concept.
2. By optimising the nozzle specifications, splay and injection angle can be adjusted to fit various engines, however, without changing the base characteristics of the spray.
3. The even shaped spray is good for the new combustion concept. It generates a suitable ball-shaped mixture close to the spark plug.
4. A new concept D-4 engine achieved higher out-put performance and wider stratified combustion area, which uses no special air flow but utilizes a slit nozzle injector and a special shaped concave cavity in piston, compared to the conventional D-4 engine.
5. A new 3L in-line 6 DISI gasoline engine with this combustion concept, installed in the vehicle with 1750kg (3675lbs) equivalent inertia weight, showed 20% better fuel economy than the conventional port fuel injection engine under the Japanese 10-15 mode.

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