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Research and Development of a New Direct Injection Gasoline Engine

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ABSTRACT

A new stratified charge combustion system has been developed for direct injection gasoline engines. The special feature of this system is employment of a thin fan-shaped fuel spray formed by a slit nozzle. The stratified mixture is produced by the combination of this fan-spray and a shell-shaped piston cavity. Both under-mixing and over-mixing of fuel in the stratified mixture is reduced by this system. This combustion system does not require distinct charge motion such as tumble or swirl, which enables intake port geometry to be simplified to improve full load performance. The effects of the new system on engine performance at part load are improved fuel consumption and reduced smoke, CO and HC emissions, obviously at medium load and medium engine speed. HC emissions at light load are also improved even with high EGR conditions.

INTRODUCTION

The distinctive feature of recent direct injection (DI) gasoline engines is to mix various operating regimes [1]~[3]. The engines are operated in stratified mode at part load and homogeneous mode at or near full load. Charge stratification is achieved by injecting fuel during the compression stroke to provide a mixture cloud around the spark plug. This enables stable combustion to be achieved while the overall mixture is ultra lean. Fuel consumption is improved by reducing pumping loss and heat losses. On the other hand, homogeneous mixtures are achieved by injecting fuel during the induction stroke. Full load performance is improved more than PFI (Port Fuel Injection) engines, because charge cooling with injection improves volumetric efficiency and knock characteristics.

Besides this strategy, a strategy to employ stoichiometric operation even at part load is also taken into consideration [4],[5]. Absence of liquid fuel in the intake port and availability of conventional three-way-catalyst give an excellent potential to reduce pollutant emissions. Higher compression ratio and engine down sizing enable vehicles to reduce fuel consumption.

Thus, DI gasoline engines have very attractive potential for improving gasoline engine's advantage of power density, and for improving their disadvantage of increased fuel consumption at part load. Recent developments of fuel systems, engine control systems, after-treatment systems and combustion systems have greatly contributed to the realization of this DI gasoline engine development [1]. Some automotive companies, including TOYOTA, have already introduced production DI gasoline engines [1]~[3].

Judging from these considerations, DI gasoline engines are promising for passenger cars. Studies of mixture preparation and combustion in DI gasoline engines have been increased recently, with stratified combustion being a major reason for engine research and development.

As combustion starts with spark discharge and flame propagation through the prepared mixture, the state of the mixture at the spark timing is one of the most important factors for better engine performance. Combustion systems for stratified mixture should be developed to operate well under homogeneous conditions as well as for good stratification. Robustness against varying engine loads and engine speeds are also important. TOYOTA has previously developed a combustion system, consisting of a high-pressure swirl fuel injector, involute concave piston and helical intake port with swirl control valve in 1996 [1]. Further studies have derived a new concept to improve both full load and part load performances. This paper reports considerations to requirements of mixture preparation, a new combustion system and test engine performance.

LEADING COMBUSTION SYSTEMS SO FAR

Spray characteristics are the major factor for control of mixture preparation. In addition to this, chamber geometry (piston, cylinder head) and charge motion are also utilizable factors for mixture preparation. Figure 1 shows the classification of leading combustion systems proposed recently.

The combustion systems that have come into practice, apply charge motion, piston geometry and swirl nozzle cone-sprays for stratified mixture preparation [1]~[3]. Figure 2 shows one of these combustion systems [1]. Since engines for passenger cars must have stable combustion in any condition, ways of not injecting fuel directly toward the spark plug are adopted. Fuel is injected once toward the piston cavity and is guided by piston wall to the spark plug with the assistance of charge motion. Vaporization and mixing of the fuel with air occur during this process. This concept requires intake port modification or a flow control valve to generate charge motion, as well as a piston with cavity. Although these requirements are not favorable for ideal homogenous operation, there are some advantages for stratified operation. Fuel behavior during the mixture preparation period can be influenced in various ways by piston cavity geometry and charge motion control. Regulation of mixture position by the cavity wall is also useful for stable combustion. Combustion systems of this kind are proposed by many companies and research facilities [6],[7].

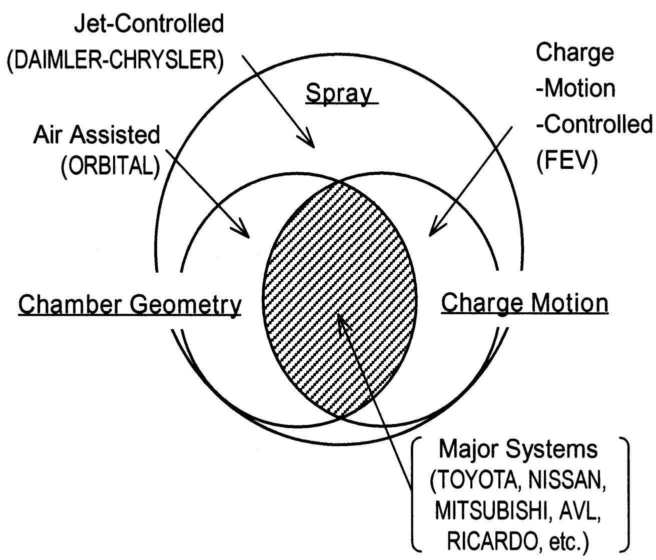


Figure 1. Classification of Combustion System

Two other methods that do not require special piston geometry for stratified mixture preparation have been proposed. One method is charge motion transport of fuel to the spark plug. Fuel is vaporized and mixes with air on its way to the spark plug. A swirl-based system is proposed in the past [8]. Recently, a tumble-based system has been proposed by FEV [9]. Although the shape of the piston of those systems is thought to be favorable for homogenous operation, requirements for strong charge motion seem to be against full load performance. Besides this, test engine results show [9] that combustion stability, including misfiring, seems to be a problem. Another is the jet-controlled method In which the spark discharges directly into the spray jet [10]. Few modifications from current PFI engines are very attractive. However, the short distance between the injection nozzle and spark plug, and short intervals between injection and spark discharge cause problems for spark plug durability and soot generation, because it is difficult to avoid the existence of many fuel droplets around the spark plug. Besides this, previous reports show that engine performance is sensitive to the injection and ignition timings, and are affected by the piston geometry [10]. Another system using an air-assisted injector is also proposed by Orbital [11].

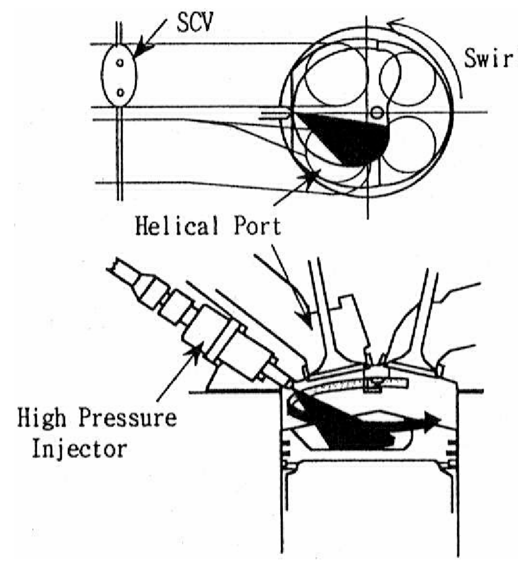


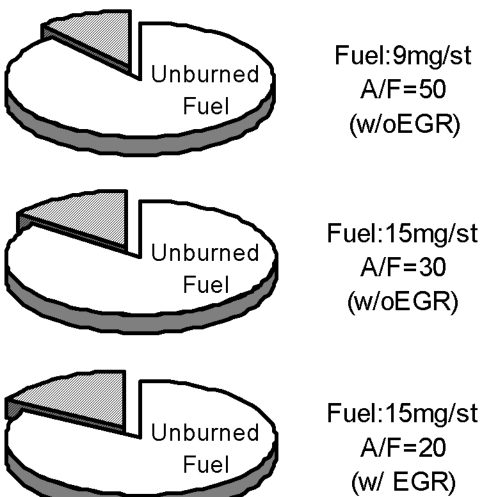
Figure 2. Conventional Combustion System

REQUIREMENTS OF MIXTURE PREPARATION

STRATIFICATION UNDER LOWER CHARGE MOTION – Almost all the combustion systems have higher demands for charge motion than PFI engines to prepare stratified mixtures. Since the cone-spray formed by a swirl nozzle has weak penetration, the role of charge motion to transport fuel to the spark plug is very important. However, special port geometry or ports with flow control valves increase flow losses to no small extent. So, the theoretical benefits of DI gasoline engines for improving full load performance cannot be fully utilized. Further, distinct charge motion increases heat losses to wall, preventing fuel consumption from being more improved. These disadvantages are notable at higher engine speed. Consequently, stratified combustion systems without the assistance of distinct charge motion is required to improve both full load performance and part load performance at middle and high engine speeds.

DISPERSION OF FUEL AND HOMOGENIZATION IN STRATIFIED MIXTURE – Flame propagation is important for recent DI gasoline engines during stratified operation, where the air/fuel ratio of the mixture should be within the flammable limits of the propagation. It is usually thought to be important for the fuel not to be dispersed, because lean mixtures are difficult to burn, and have resulted in light load HC emissions that have been one of the major problems of DI gasoline engines.

The state of the mixture preparation in the conventional combustion system was examined. The tested system was the swirl-based system with cone-spray [1]. Figure 3 shows the ratio of unburned fuel in the HC emissions under stratified operation, analyzed by gas chromatograph. Almost 90% of HC emissions are unburned fuel at light load. The rest of those are partially burned HC. The ratio of unburned fuel is more than 80% at medium load even in the operation with EGR. These results indicate that most of HC emissions are from over-diluted fuel or isolated fuel torn into pieces that is due to over-dilution. This confirms the importance of not forming an over-lean mixture.



Engine Speed:1200rpm

Figure 3. Ratio of Unburned Fuel in HC Emissions

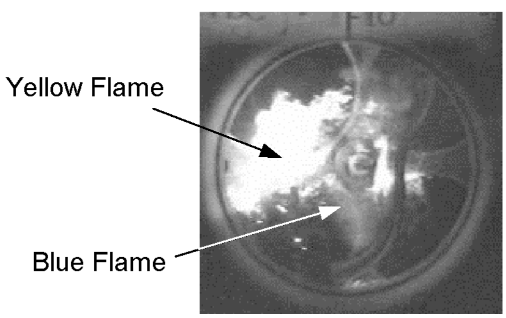
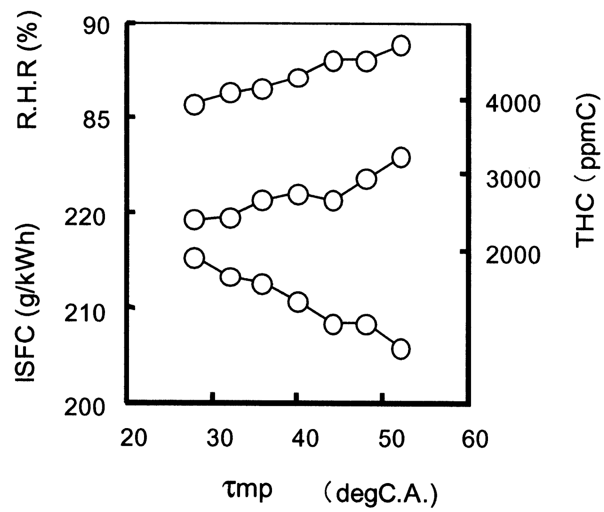


Figure 4. Flame in Stratified Operation

Conversely, as the stratified mixture stays locally under-mixed, the fuel should be mixed well with air at this point. Figure 4 shows a flame image of stratified combustion in the conventional DI gasoline engine. The blue and yellow flames suggest flame propagation through heterogeneous air/fuel ratio. Yellow flame shows the under-mixing of fuel. Although this is the result of fuel stratification for reliable inflammation under ultra lean operation and reduction of over-diluted fuel, combustion in the rich mixture is undesirable because of a significant amount of incomplete combustion products. As most of these products are oxidized during the expansion and exhaust stroke, many incomplete combustion products do not leave to the end. The problem is that the amount of heat released near TDC decreases because of heat loss due to incomplete combustion. These phenomena are notable during conditions where the engine is operated under higher load or higher engine speed, preventing fuel consumption from being more improved.

Figure 5 shows the effects of mixture preparation period (τ_{mp}) on engine performance at medium load. The τ_{mp} is the period from the start of injection until spark discharge. HC emissions increase as τ_{mp} increases, because mixing of fuel with air progresses. However, fuel consumption (ISFC) decreases. The reason is that long τ_{mp} decreases rich mixture formation and increases combustion efficiency near TDC. This is confirmed by the fact that ratio of heat release {R.H.R., (integration of heat release rate)/(heating value of fuel)}, that is to say the maximum integral value of heat release rate, increases in proportion to τ_{mp}.



Engine Speed:1200rpm,Fuel:14.7mg/st

Figure 5. Effects of Mixture Preparation Period

Thermodynamic considerations indicate that R.H.R does not decrease even if flame propagates through a fuel-rich mixture, as long as burned gases mix with the surrounding air quickly like the diesel combustion process. However, mixing with air in DI gasoline engines progresses slower than the case of diesel engines. According to the theory of momentum [12], the amount of air induced into the fuel jet can be calculated by equation (1).

$$d(A/F)/dt = c \cdot \underline{(\rho a^{1.7} \cdot vf^{2})^{0.25}} \cdot t^{-0.5} \quad (1)$$

Although the equation (1) is developed for a diesel spray, it is thought to be available to high-pressure gasoline spray because of fine droplets. It has been validated by comparison between calculated spray lengths by this theory and experimental results. Figure 6 shows the comparisons of various types of sprays. The tested swirl nozzle forms solid cone spray. The calculated spray lengths give good agreement with the results of experiment, showing that equation (1) is valid for DI gasoline sprays.

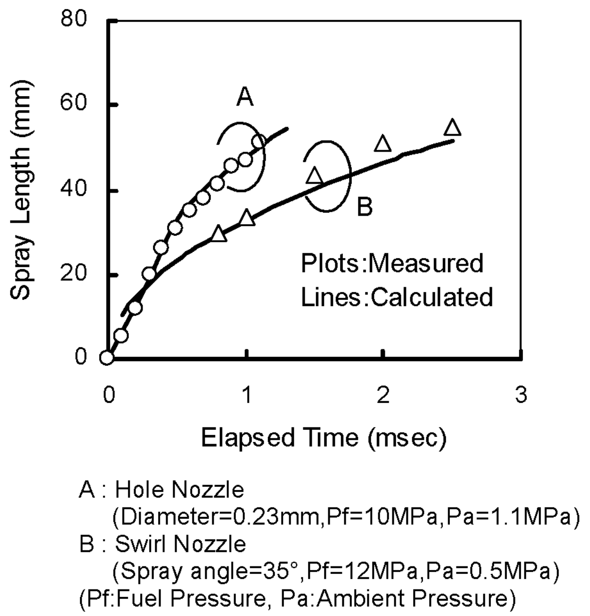


Figure 6. Comparisons of Spray Length

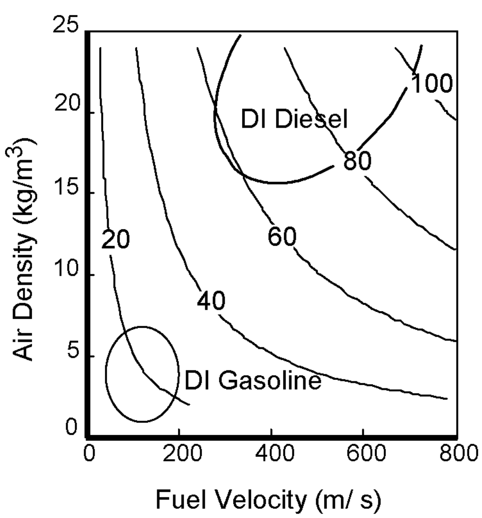


Figure 7. Comparison of Air Induction Speed

Figure 7 shows the contour lines of the numerical values of the underlined portion of the equation (1). It shows the effects of air density and spray jet speed. The larger the value is, the larger the air induction speed becomes. Circles in the figure show each DI engine's characteristic. The air induction speed of DI gasoline engines is from 1/3 to 1/5 of the case of DI diesel engines. It is thought that the large period from start of injection to spark advance is not only due to the fuel travel to the spark plug, but also from slow mixing speed. Slow mixing of fuel with air implies slow mixing of burned gases with air.

The above shows that fuel should be mixed well before spark discharge, to get high combustion efficiency after flame propagation. It is particularly important at higher load and higher speed because the permissible time for mixture preparation is short.

NEW COMBUSTION SYSTEM

The aims of the new combustion system are:

- Mixture preparation without depending on distinct charge motion
- Decreased under-mixing and over-mixing of fuel, and robustness against varying engine loads and engine speed

As mentioned previously, most of the combustion systems prepare stratified mixtures with charge motion. One of the differences in mixture preparation with or without charge motion seems to be engine speed response. Since present fuel systems are unable to control fuel pressure like diesel fuel systems, spray characteristics are fundamentally independent to engine speed. On the other hand, the time allowed for mixture preparation decreases in proportion to engine speed. Consequently, there are some differences in mixture preparation with engine speed. The differences are investigated from the point of view of spray penetration and fuel dilution.

Figure 8 shows the typical situation of mixture preparation with and without charge motion control. Each line in the figure represents differing engine speeds. As the required travel distance of fuel is thought to be independent on engine speed, fuel must travel faster or traveling time must be increased if engine speed becomes high. Faster fuel delivery can be achieved by charge motion control, because charge motion increases with the engine speed. However, induced air into the spray seems to be unchanged. Far from that, a decrease of induced air is conceivable because of lower relative velocity, causing under mixing at higher engine speed.

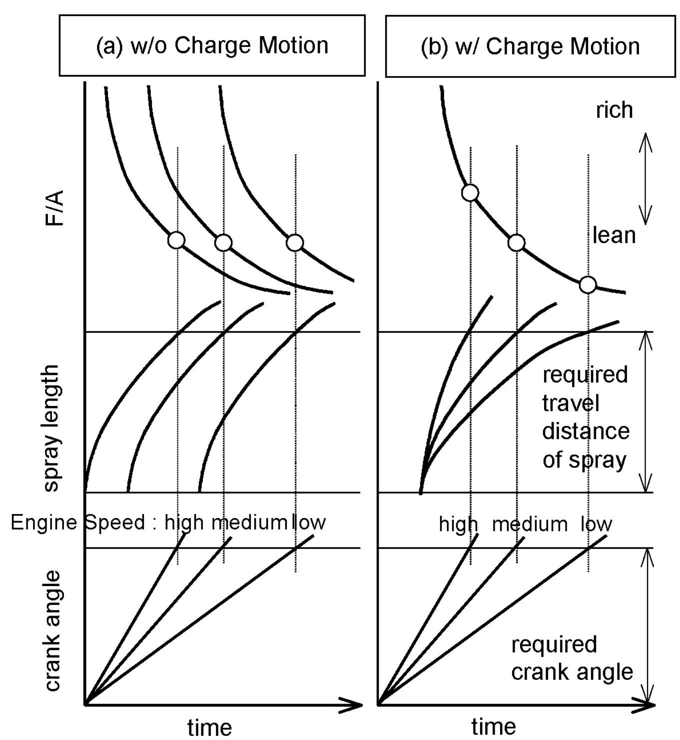


Figure 8. Influences of Charge Motion

Increased travelling time can be achieved by advance of injection timing. Although the required crank angle for mixture preparation becomes longer, mixing with air is ensured. It is important for robustness to keep fuel transfer and mixing with air well balanced. The concept without charge motion has the ability to meet this requirement. Piston movement, intervention of piston wall and differences in turbulence don't make this simple in practice. However, it is well understood that mixture preparation without charge motion has potential for not only managing both stratified and homogeneous operations well, but also for improving the robustness against the engine speed.

The new concept without charge motion requires different spray characteristics as before. Suitably large penetration and high mixing ability of spray are needed for the required injection timing not to advance too far at higher engine speed. The cone-sprays used in conventional DI gasoline engines are currently suitable for ultra lean stratified operation at low load because of its characteristic of contracting in the high ambient pressure [13]~[15]. In summary, a cone-spray is not suitable for this new concept for the following:

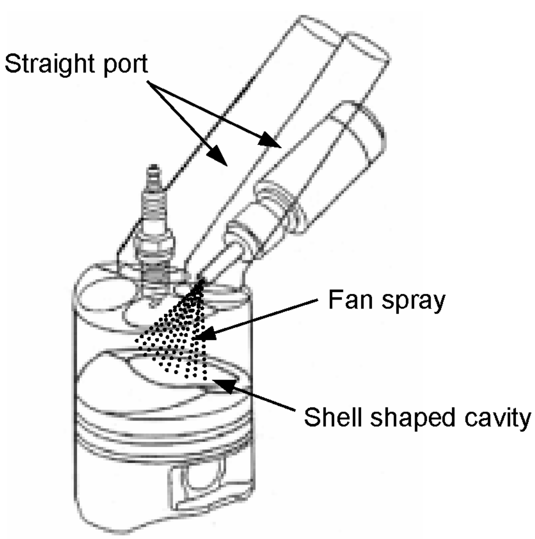


Figure 9. Combustion System

- The contracting characteristic means that fuel moves to the inside of the spray. Fuel distributions are believed to be fuel-rich inside and fuel-lean outside in the case of late injection. HC emissions and cycle-by-cycle variation of combustion increase greatly if injection timing is advanced to eliminate under-mixing of fuel.
- Adequate dispersion of fuel is hard to realize at higher load and higher engine speed because of the contracting characteristic.
- Large spray angles make penetration small. It requires charge motion assistance.

So, a new combustion system is developed using a fan-shaped spray. Figure 9 shows the outline of this system. The system puts fan-spray characteristics to practical use. The characteristics are:

- A thin, fan shape to enable fuel to be well dispersed and to mix with air uniformly.
- Small side view angle enables the fuel to move faster than cone spray.

Fuel is injected toward the piston crown, on which a shell shaped cavity is made for the spray to be rolled up near the spark plug.

MIXTURE PREPARATION AND COMBUSTION

Spray Characteristics – The fan-spray is formed by a slit nozzle of which the shape is rectangular and longer sides are diverged from the inside to the outside. Shorter sides of the tested nozzles are from 0.1mm to 0.2. Figure 10 shows the schematic drawing of the slit nozzle. Figure 11 shows an example of a fan-spray. Concentric circles of spray are observed in a front view, and a thin spray is observed in a side view. A leading slug of liquid, which is one of the defects of swirl nozzle, is not observed at all.

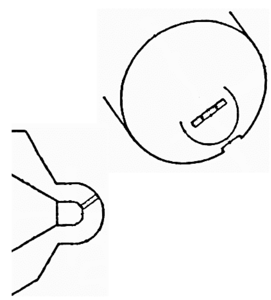


Figure 10. Slit Nozzle

The new combustion system requires two important spray characteristics. The first is homogeneity of fuel distribution in a spray. Figure 12 shows line-of-sight fuel distributions that are measured from the intensity of light through the spray [16]. It shows that fuel mixes with air equally toward the downstream of the spray to homogenize fuel concentration especially at high ambient pressure. It keeps fuel from under-mixing in stratified operation. Another characteristic observed is that the ambient pressure does not change the spray angle in a front view, but the other spray angle (in a side view) becomes large as ambient pressure increased.

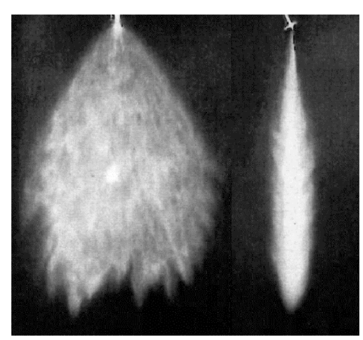


Figure 11. Image of Fan Spray

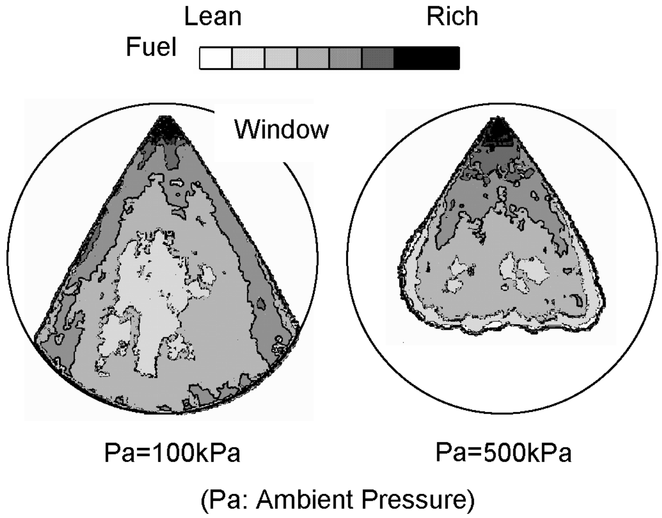


Figure 12. Fuel Distribution

The second characteristic is spray penetration to move the spray towards the spark plug. The fan shape is more favorable for large penetration than a cone-spray. Figure 13 shows the effect of spray angle on spray penetration in each case for a cone-spray and fan-spray. The spray angle of the fan-spray is the larger one. The line in the figure shows the border of the spray angle that forms the same penetration for each spray. These results are calculated from the theory of momentum [12]. The cone-spray is assumed as a solid cone. This figure shows that the fan-spray has larger penetration than a cone-spray for the same spray angle. The difference becomes greater as the spray angle becomes large. Although it may be difficult to compare fan-sprays and cone-sprays formed by a swirl nozzle (because cone-sprays contract in high ambient pressure or its shape can breakdown), experimental results show that the spray lengths of a fan-spray (spray angle:60°) and a cone-spray (spray angle:30°) formed by swirl nozzle are almost the same, as shown in figure 14. It is as same as the results of figure 13. Since the cone-angle of a swirl nozzle is usually more than 40° in most DI gasoline engines, spray penetration of a fan-spray is always larger than a cone-spray.

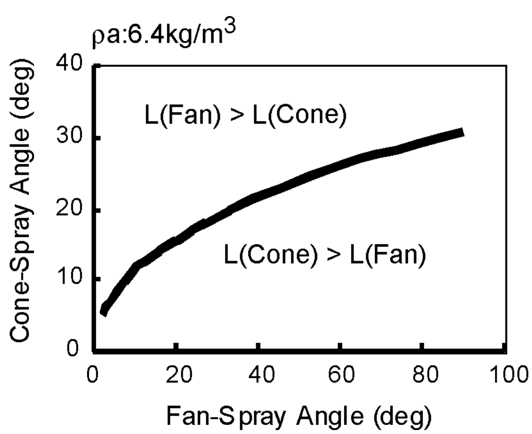


Figure 13. Comparison of Spray Length

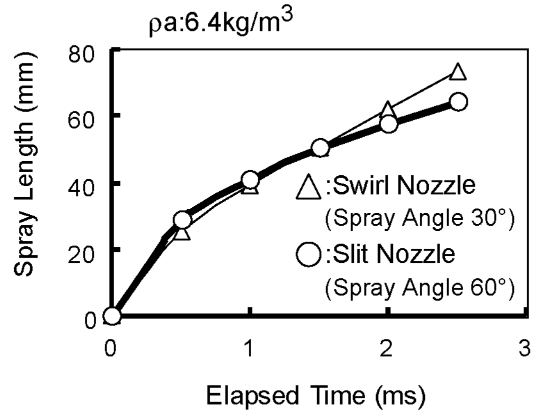


Figure 14. Spray Length

An another important spray characteristic is the droplet size. The SMD (Sauter Mean Diameter) values of the droplets are measured by laser diffraction. Table 1 shows the average SMD at 40mm downstream from the nozzle. The results show that the slit nozzle provides highly atomized fuel spray.

Table 1. Droplet size

Ambient Pressure (MPa, Absolute)	SMD (μm)
0.1	10
0.5	15

Mixture Preparation – Mixture preparation in the cylinder, calculated by 3-D CFD [17], is shown in figures 15 and 16. Figure 15 shows velocity and borderline of a fuel concentration in a vertical cross sectional view including the spark plug at each crank angle. Injected fuel impinges the bottom of the cavity at first, then moves to the spark plug along the piston wall. During these processes, shear flow generates a large eddy at the outer and the plug sides of the spray as well as entraining surrounding air. As the eddy moves with the spray, fine fuel droplets and vaporized fuel are engulfed, and the spray increases its thickness. Mixture preparation progresses as if it were rolled up. As the piston moves up, squish flow from the exhaust side joins the spray flow. Near TDC a kind of round shape mixture is apparent in the cross sectional view. The eddy finally reaches the mixture and revolves in it, homogenizing the fuel distribution, keeping the mixture shape until spark discharge. Figure 16 shows a horizontal cross sectional view at 20°BTDC (section A-A in Figure 15). The shape of the cavity wall opposite to the nozzle is formed for the spray to turn direction toward the inside of the cavity. It helps the once diverged fan-shape mixture to fold back toward the center of the cavity. That is to say, the mixture away from the spark plug moves spirally toward the center of the cavity. These behaviors form an ellipsoidal shaped mixture around the spark plug at the time of spark discharge. Mixture preparation processes are similar for various loads and engine speeds. The differences are that longer mixture preparation periods make the mixture spread toward the injector side, making the ellipsoidal mixture large at higher load for example.

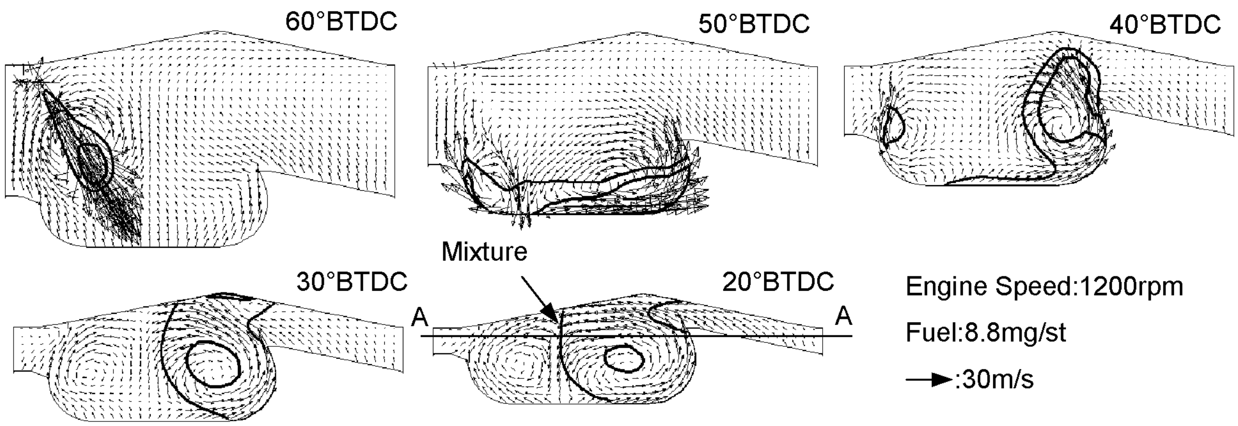


Figure 15. Mixture Formation Process

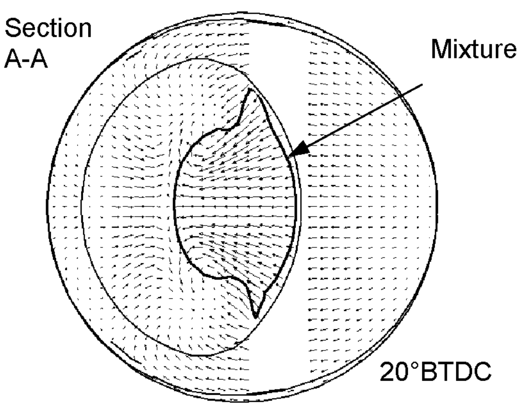
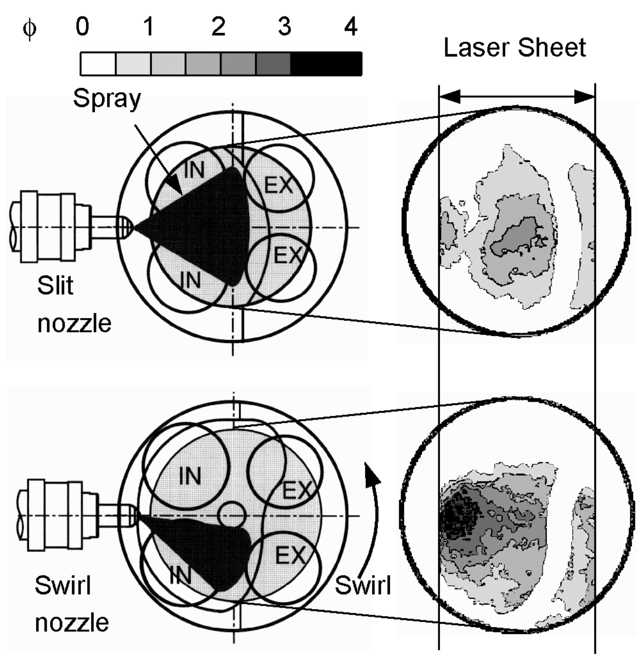


Figure 16. Velocity and Fuel Distribution



Engine Speed:1200rpm, Fuel:8.8mg/st

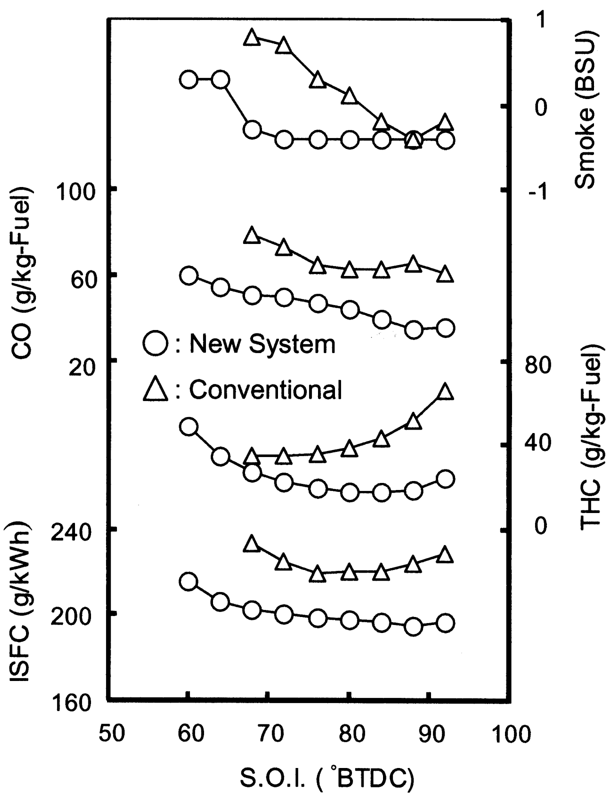
Figure 17. Comparison of Fuel Distribution

Figure 17 shows the fuel equivalence ratio distributions at the time of ignition in the horizontal cross section of the chamber in the spark plug gap, that are measured by LIF (Laser-Induced Fluorescence) [18]. The figure compares fuel distribution of the new combustion system with that of the conventional combustion system. Mixture preparation periods (from start of injection to spark advance) of both system are the same. Rich mixtures with equivalence ratios exceeding 2 are observed for the conventional system. The equivalence ratio of the richest mixture partially exceeds 2.5. On the other hand, the equivalence ratio is less than 2 in the case of the new combustion system. It is proved that the new combustion system prepares the mixture quickly and decreases under-mixing of fuel. It is advantageous to extending the stratified operation region.

<u>Combustion</u> – Effects of the new combustion system were examined using a single cylinder test engine. The engine specifications are shown here.

- Bore × Stroke … 86mm × 86mm
- Fuel pressure … 12MPa
- Spray angle … 60deg
- Compression ratio … 11

One of the major benefits is full load performance because of simple port geometry, which are reported in another paper [19]. Part load performances are reported in this paper. The major purpose of this concept for stratified operation is to reduce under-mixing of fuel especially at high load and high speed in the stratified operation region.

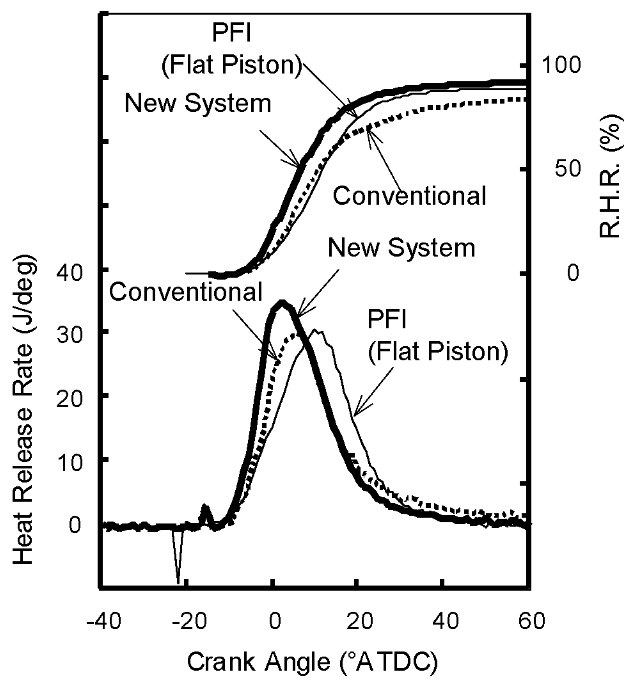


Engine Speed:2400rpm Fuel:17.5mg/st, w/o EGR

Figure 18. Part Load Performance

Figure 18 shows the comparisons of fuel consumption and exhaust emissions between the new combustion system and the conventional one at middle load and middle engine speed. The x-axis is start of injection (S.O.I.). The new combustion system reduces smoke, CO, HC emissions and fuel consumption. Reductions of smoke and CO emissions indicate a reduction of under-mixing of fuel, while reduced HC emissions indicate reduction of over-mixing of fuel. These results show that the mixture prepared by the new system becomes more homogeneous. Another difference is sensitivity of injection timing on HC emissions. HC emissions increase as the injection timing advances in the conventional system. The opposite result is found in the new system. Although the differences of HC emissions are small at retarded injection timing, the lowest HC emissions of the new system are one-half of those of the conventional system. Fuel consumption of the new system is smaller than that of the conventional system. It is confirmed that reduction of under-mixing fuel contributes greatly to fuel consumption. There is also a difference of optimum injection timing which is thought to be due to whether a system depends on charge motion. The mixture may move faster than mixing with air in the conventional system.

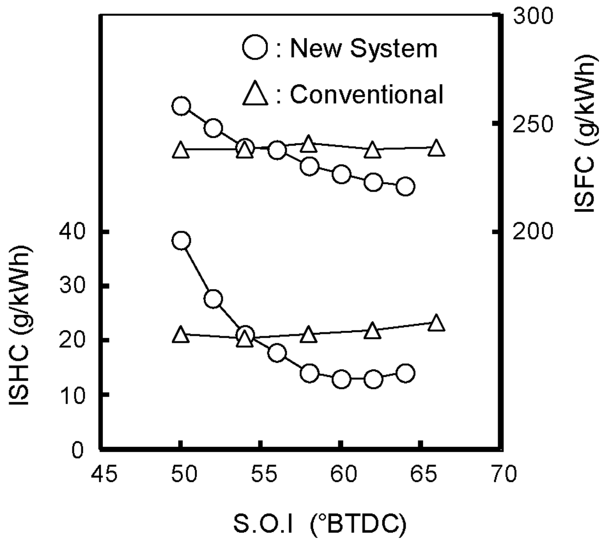
The fuel consumption advantages of the new system were investigated by thermodynamic analysis. Figure 19 shows the comparison of the heat release rates for a PFI engine, conventional DI engine and for the new system. The heat release rate for stratified combustion has short ignition delay, large heat release at the beginning and slow burning at the end of the process compared to homogeneous combustion by PFI. Although this type of combustion process is kept in the new system, burning velocity is faster than that of the conventional system. In particular, the ratio of fuel that burns slowly at the end of the combustion process is decreased. Consequently, the ratio of heat release (R.H.R.) of the new system is larger than those of the conventional system and PFI, resulting in the improvement of fuel consumption.



Engine Speed:2400rpm Fuel:17.5mg/st, w/o EGR

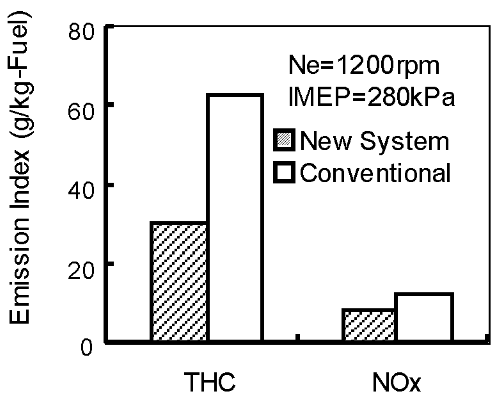
Figure 19. Heat Release Analysis

Next, HC emissions and fuel consumption at light load and low engine speed are shown in figure 20. As mentioned before, most HC emissions are unburned fuel. Although a system that produces a stratified mixture by dispersing fuel like this concept is expected to be disadvantageous at light-load, experimental results show that HC emissions of the new system actually decrease if the injection timing is proper. Figure 21 shows the influence of EGR. The new combustion system has very low HC emissions even in such high EGR conditions.



Engine Speed:1200rpm, Fuel:8.8mg/st, w/o EGR

Figure 20. Part Load Performance



Engine Speed:1200rpm,Fuel:8.8mg/st, w/ EGR

Figure 21. Emissions

CONCLUSIONS

A new combustion system that produces a stratified mixture by a fan-spray and shell-shaped piston cavity has been developed. This system does not require special charge motion, such as tumble or swirl. The following are features of this mixture preparation and the test engine results.

1. Characteristics of the spray are:
   - Large penetration compared to cone-spray
   - Uniform fuel distribution in the spray
   - The spray keeps its shape and uniformity of fuel distribution even if ambient pressure changes.
2. The eddy induced by the shear flow of the spray and cavity shape form an ellipsoidal stratified mixture while rolling up the originally thin and fan-shaped spray.
3. The new combustion system reduces under-mixing of fuel. LIF measurements and flame observations confirm this effect.
4. The new combustion system improves fuel consumption as well as smoke, CO and HC emissions at middle load and middle engine speed.
5. Thermodynamic analysis shows that the new combustion system makes the burning velocity fast, especially at the end of combustion process. This causes increased heat release near TDC.
6. HC emissions at light load are lower than that of conventional DI combustion systems, even in the condition of high EGR.

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