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QUANTITATIVE ANALYSIS OF MIXTURE PREPARATION PROCESSES IN NEW DIRECT-INJECTION SPARK IGNITION ENGINES

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Visualization plays an effective role in the establishment of a new combustion concept by helping to find the optimal results quickly among many different parameters and contributing to a shorter development period. Laser-induced fluorescence, Raman scattering and infrared absorption were used to measure the air/fuel ratio quantitatively in a third-generation direct-injection gasoline (DIG) engine with a spray-guided mixture formation process and compar- isons were made with the mixture formation concepts of the first- and second-generation DIG engines. The optimum combination of fuel spray, gas flow and combustion chamber configu- ration was found to be different for the three generations of DIG engines. The characteristics of the stable combustion region for obtaining higher thermal efficiency and cleaner exhaust emissions differed among the three mixture formation concepts.

Key Words: Combustion, Gasoline Engine, Nozzle, Laser-Aided Diagnostics Optical Mea- surement

1.Introduction

One method of improving the thermal efficiency of internal combustion engines is to apply a lean combus- tion process, an ultimate form of which is stratified-charge combustion. With stratified-charge combustion, a com- bustible mixture is prepared only in the vicinity of the spark plug under low engine loads to accomplish combus- tion and obtain torque reliably even if the air-fuel ratio in the region near the inlet valves is leaner than 40:1. This combustion concept has already been incorporated in en- gines used on production vehicles offered by several man- ufacturers in Japan(1) – (3) and it contributes to reducing at- mospheric emissions of carbon dioxide (CO_2) in city driv- ing.

The preparation of a stratified mixture in a specified area of the combustion chamber within a limited time in- terval requires an optimum combination of three factors, i.e., gas flow, fuel spray and combustion chamber configu- ration, which are three important elements of this combus- tion

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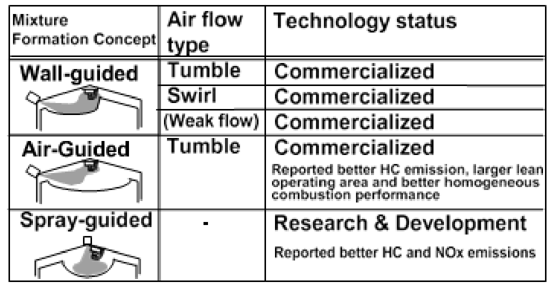
concept. Visualization or quantitative measurement of the mixture formation process in the combustion chamber is a very effective way to investigate the optimum combi- nation, and such techniques are also effective in shorten- ing the development period for optimizing the combustion concept.

It is said that three generations of direct-injection gasoline (DIG) engines have been developed so far. A wall-guided mixture formation process was used in the first-generation engines manufactured in Japan. At the present time, second-generation DIG engines using an air- guided process have been commercialized both in Japan and overseas(4) and third-generation engines with a spray- guided concept(5) are now on the verge of being released. This study focused in particular on the third generation of DIG engines and the essential aspects of the spray-guided concept were made clear by applying quantitative meth- ods of measuring the mixture concentration. Differences between the spray-guided process and the earlier concepts were also made clear. In short, stratified charge combus- tion involves localized mixture formation, and tracing the mixture behavior in the formation process is indispensable to determining the best way of accomplishing the combus- tion concept. Figure 1 shows the overview of three forma- tion concepts, so-called wall, air and spray guided concept and today's information about the charge in market.



Mixture Formation Concept	Air flow type	Technology status
Wall-guided	Tumble	Commercialized
	Swirl	Commercialized
	(Weak flow)	Commercialized
Air-Guided	Tumble	Commercialized Reported better HC emission, larger lean operating area and better homogeneous combustion performance
Spray-guided	-	Research & Development Reported better HC and NOx emissions

Fig. 1 Overview of three mixture formation concepts

Laser-induced fluorescence (LIF) was used to obtain 2-D visualizations of the mixture formation process, and particle image velocimetry (PIV) was employed to visu- alize in-cylinder flow fields quantitatively. In addition, changes in the air-fuel ratio in the vicinity of the spark plug gap were measured continuously by means of an in- frared absorption technique developed in-house at Nissan as an onboard measurement method. Based on those re- sults, a quantitative analysis was made of the stable com- bustion region, defined by the ignition timing and fuel in- jection timing, which is the most important aspect of mix- ture formation with the third-generation spray-guided con- cept. The conditions essential to the viability of this con- cept were made clear by using LIF to obtain highly accu- rate, quantitative measurements that were then verified by Raman scattering method.

2. Laser-Based Measurement Methods

During the 1990s, various companies proposed differ- ent lean-burn combustion concepts or lean-burn engines developed by the application of laser Doppler Velocime- try (LDV) and PIV to measure the in-cylinder gas flow(6). Moreover, in the latter

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half of the 1990s, different man- ufacturers and universities proposed various methods of obtaining 2-D visualizations of the mixture concentration field needed to accomplish stratified-charge combustion in DIG engines(7).

Underlying that work was the knowledge acquired concerning the self-quenching effect due to concentration of dopant and the effect of quenching by oxygen in con- nection with the use of LIF as a non-contact measurement technique to capture the mixture concentration under the constantly changing high temperatures and high pressures present in an engine. Furthermore, an understanding was gained of the various effects on fluorescent intensity due to the latent heat of vaporization and the residual gas temper- ature, owing to the use of direct injection.

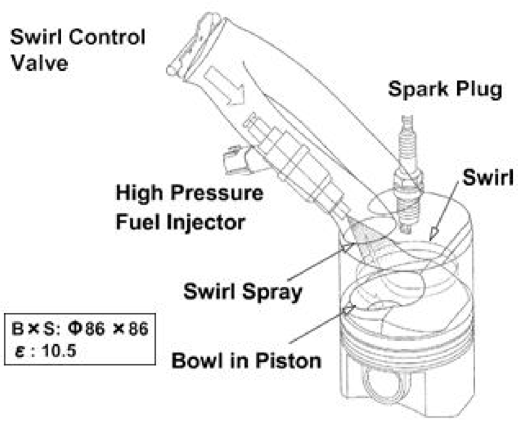

Fig. 2 Basic configuration of combustion chamber

Japanese vehicle manufacturers began to put DIG engines on the market in 1996. The mixture formation concept incorporated in the first-generation DIG engines at that time was the wall-guided process. Mitsubishi's wall-guided process using tumble flow had an inverted intake port, and this wall-guided system was generally referred to as GDI (gasoline direct injection). A swirl fuel injector that produced fuel pressure of 5 MPa was used, and a bowl-shaped cavity was provided in the piston crown directly below the intake valve. Toyota and Nissan DIG engines also adopted the wall-guided concept. One strong point of the wall-guided process is that it transports the fuel spray reliably to the vicinity of the spark plug. The gas flow makes use of swirl, and all three compa- nies initially employed a swirl fuel injector to discharge the spray. However, Toyota later adopted a compressed spray pattern, called a fan spray, without any intensifica- tion of swirl. That resulted from concerted efforts to cre- ate a mixture cloud with a uniform concentration, and nu- merical calculations were also introduced into fuel spray analysis(9). It might be better be called pure wall-guided concept.

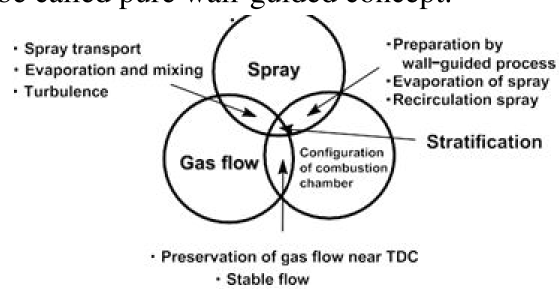

Fig. 4 Three elements of combustion control

In contrast to those first-generation DIG engines, in the middle of 2001 Honda released a new information of a DIG engine with the wall-guided process and central injection(10). The engine was designed with a swirl fuel injector provided directly above the pent-roof combus- tion chamber. Compared with the first-generation process, what advantages or issues does this different wall-guided system or the air-guided concept have? Figure 4 illustrates the three factors of stratified-charge combustion, namely, the fuel spray, gas flow and combustion chamber config- uration, and indicates the roles each one plays in double or triple overlapping regions(11). Although all three circles are drawn in the same size, the respective roles played by each factor in the three generations of mixture formation concepts are not the same, as can be understood from the name of each process. The roles of double and triple over- lapping arias among them are shown above the arrows.

Additionally, the significance of the triple overlap- ping region is that the viability of charge stratification de- pends solely on the optimum combination of these three factors. In other words, the preparation of a stratified mix- ture is a very difficult issue that requires a thoroughgoing effort to combine these factors in exactly the right way. It should be noted that engines with a pure spray-guided process have yet to be commercialized.

4. Measurement of Mixture Concentration Fields by LIF and Infrared Absorption

This section describes the characteristics of the wall- guided and air-guided concepts based on direct and con- tinuous measurements of the mixture formation process obtained by infrared absorption method. A schematic di- agram of the experimental apparatus(12) used for infrared absorption is shown in Fig. 5, and examples of the exper- imental results obtained are given in Figs. 6 and 7(12). In the middle of Fig. 6 shows that, in the case of the wall-guided process, a suitable mixture forms after a certain in- terval has elapsed following the end of injection. That in- terval is used for evaporation of the fuel spray and mixing with the air. The mixture concentration varies cycle-to-cycle, and the average concentration is leaner and varies more with an earlier injection timing. This is attributed to greater mixing with the air as the transport path of the fuel spray via the piston crown to the spark plug becomes longer. In other words, if air-fuel mixing is excessively promoted, it increases the cycle-to-cycle variation of mix- ture concentration. In contrast, for example, at a crank an- gle of 40◦ before top dead center (BTDC) in lower part of Fig. 6, corresponding to the ignition timing, the air- fuel ratio is slightly richer than a stoichio-metric mixture. The results of the LIF measurement made simultaneously clearly show the stratification process of the mixture. The

1.30 μm diode laser in Fig. 5 produces infrared light that is not absorbed by the fuel and is used as a reference sig- nal for judging a reduction of light due to the presence of fuel droplets in the measured optical path or to stain on the glass surface, thereby facilitating reliable judgment of absorption by the mixture.

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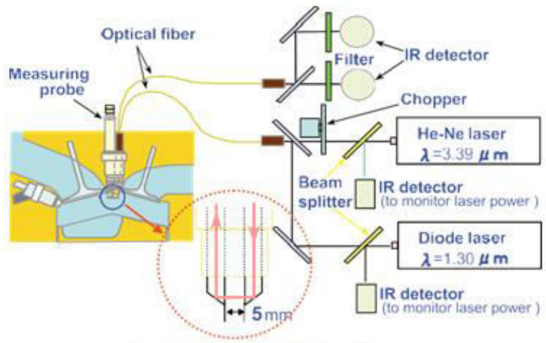

Fig. 5 IR absorption system (in house)

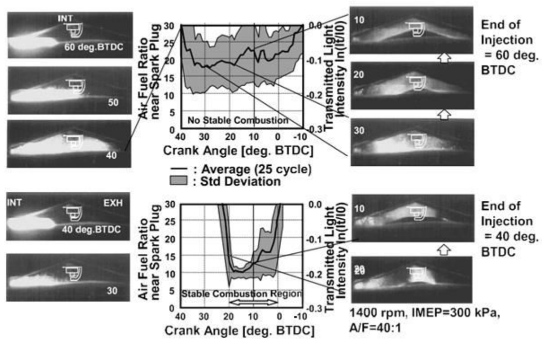

Fig. 6 Wall-guided mixture formation process

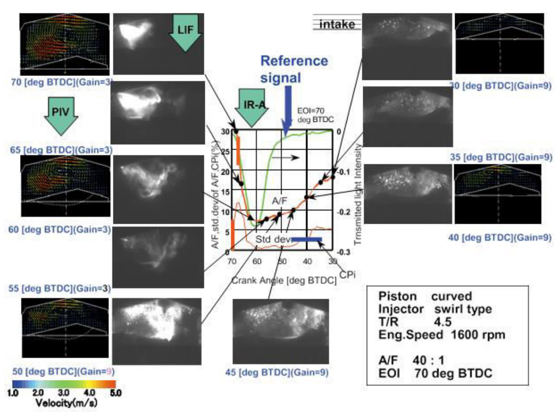

Fig. 7 Air-guided mixture formation process

5. Comparison of Raman Scattering and LIF

Raman scattering is a method of obtaining the inten- sity of scattered light corresponding to the concentrations of stable molecules. This is accomplished by the change in the vibrational or rotational state of the molecules them- selves corresponding to the incident wavelength (photon energy), while avoiding interference with the strong in- cident wavelength, i.e., Rayleigh line, by making use of slight changes in the incident energy level. In general, Ra- man scattered light on the stronger Stokes side is used in this method. From the space into which the energy is in- jected, the scattered light of specific coexistent molecules present simultaneously can be obtained respectively as light at different wavelengths on the basis of a single Rayleigh line. While the principle is clear, the challenge is to obtain signals with a good signal-to-noise (SN) ra- tio for light that is markedly weaker than Rayleigh light (wavelength of 248 nm from Kr-F Excimer Laser). That difficulty can be surmounted using various types of opti- cal filters, among other means.

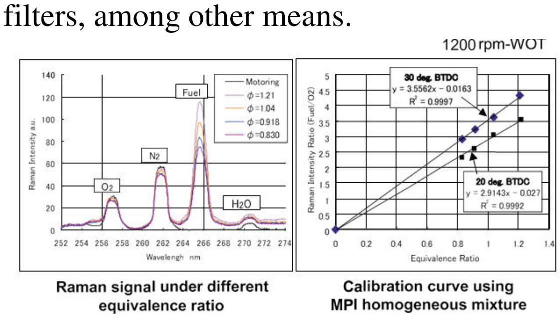

Fig. 8 Raman scattered light intensities for various molecules

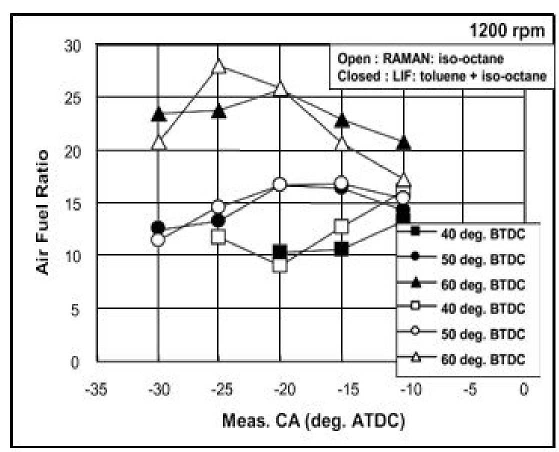

Fig. 9 Comparison of air-fuel ratios with spray-guided process

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6.Characteristics of Spray-Guided Concept

While preparation of the fuel spray in the center of the combustion chamber naturally requires effective coor- dination with the ignition timing, it is necessary to ignite a gaseous-phase spray. As will be discussed later, such a spray has a narrow ignitable range. Figure 10 shows time histories of the air-fuel ratio obtained at two arbitrary points in a spray injected from directly overhead. As is evident from the figure, the air-fuel ratio time histories are different at the two points. Point 1 is close to the one of six sprays from the injector and it touched the periphery of the spray at 14 degree BTDC. Point 2 locates far from the injector center and the position is above the edge of a shallow bowl on the surface of the piston crown. An ig- nitable air-fuel ratio is seen at Point 1 right after injection at 12 deg. BTDC (1st orange circle), but it soon becomes overly lean and then again returns to a combustible air-fuel ratio at 3 deg. BTDC (2nd orange circle). In other words, ignition is possible at two different times. The first time is for the spray of the spray-guided process and the second time is for the wall-guided spray that transits the bowl in the piston crown. Spray with high fuel pressure of 20 MPa has a strong penetration and its shows the turnaround be- havior after the collision against the piston crown surface.

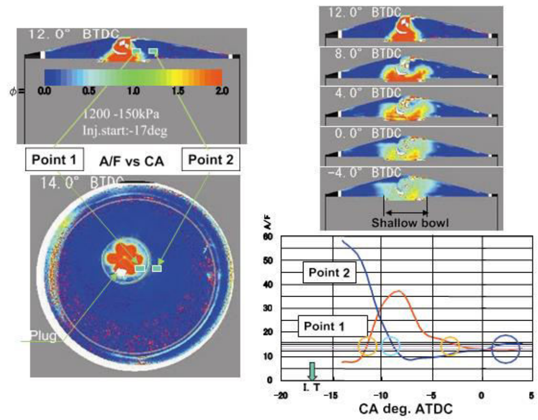

Fig. 10 Charge in air-fuel ratio with spray-guided concept

In Fig. 10, on the other hand, at Point 2 outside the spray, only the wall-guided spray that transits the piston crown bowl is ignitable at 9 deg. BTDC(which is shown in blue circle). The behavior of this spray that transits the piston crown bowl is also due to penetration of high- pressure spray under the pressure of 20 MPa. This pene- tration makes the mixture upward from the edges of the shallow bowl provided in the piston crown. Finally, both of the points show the air fuel ratio of about 15.0 in vio- let circle. This means that the flame can well propagate under this value of mixture prepared near the spark. This value is ideal for ignition and combustion but timing is too late for the best thermal efficiency. If this equivalence ra- tio value of approximate 1 is prepared before TDC timing properly, the combustion is carried out under ideal air fuel ratio mixture.

7. Conclusions

(1) Laser applied techniques such as PIV, LIF, IR- Absorption method are used to understand the flow, spray and mixture preparation process of three kind of stratifica- tion concepts such as wall-guided, air-guided and spray- guided concept in Direct Injection Gasoline (DIG) Engine. Each method facilitated to know the roll of flow field, spray and combustion chamber configuration for aiming at the stratification of mixture in combustion engine.

(2) Raman scattering was used to compensate the quantitative accuracy of air-fuel ratio measurements ob- tained by LIF. In other words, this non-intrusive measure-ment approach makes it possible to quantify the air-fuel ratio at any arbitrary location in the combustion chamber and provides a guideline for determining the combustion concept. This no-intrusive method has strong effect on the spray-guided concept because the interaction between this spray and spark plug electrodes is very delicate. An intru- sive method is not suitable for measuring the air-fuel ratio in this process.

(3) An investigation was made of the differences in the stratification process of the mixture formation con- cepts used in three generation of direct injection gaso- line engine. As a result, it was found that the optimum combination of fuel injection and ignition timings differs for each concept. The roll of flow field and combustion chamber communication is strong in wal-guided concept. The roll of flow field is also stronger in air-guided con- cept. Therefore, both concepts have a restriction for strat-ification because they strongly depend on the flow field. But it fundamentally changes from cycle to cycle under wide driving condition. This demerit restricts the opera-tion range of stratification driving. But spray-guided con- cept does not have a concrete demand for flow field. Spray

must always aim at the electrodes, directly.

(4) The spray-guided process includes elements re- sembling the wall-guided concept and pure spray-guided concept. Both of them provide a stable combustion region, but it has rigorous requirements for fuel atomization and mixing with the air. This requirement gets weaker in the quasi-wall guided behavior. When the spray returns after the collision with the piston crown surface, this spray pre- pares the gas phase mixture in the vicinity of spark plug and its return position is controlled by the edge of shallow bowl worn in piston crown surface. But pure spray-guided concept can operate just after the injection end and this performance will make it possible to operate wider engine speed and load condition without strong restriction of flow field and combustion chamber configuration. Finally, it is thought that the true benefits of central injection coupled with a spark plug depend on those fuel spray requirement and on the fuel spray quality.

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