

Optimization of Combustion Chamber for 2.0L Direct-Injection Gasoline Engine

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ABSTRACT

A center injection system in which a high-pressure fuel injector is located in the center of the combustion chamber has been employed in a direct-injection engine, significantly improving fuel economy and emissions performance in the direct injection stratified charge (DISC) range. Ensuring the stable formation of a combustible mixture around the spark plug at the appropriate time is the most important element in achieving stable combustion in the DISC range. During the development of the engine, a variety of methods were used to measure mixture distribution, including visualization using Laser Induced Fluorescence (LIF) and infrared absorption analysis to measure the air-fuel ratio around the spark plug, and CFD simulations were conducted to analyze mixture distribution and in-cylinder flow, enabling analysis and evaluation of the combustion process. These analyses enabled the design of an original piston cavity form with reference to the fuel spray characteristics of the center-positioned high-pressure injector. This has ensured the stable formation and maintenance of a compact combustible mixture around the spark plug, enabling the achievement of a high lean combustion limit in stratified combustion and significantly reducing fuel consumption.

1. Introduction

Increasing concern over global environmental issues have led to demands for improved automotive fuel economy and decreased automotive emissions. The achievement of stratified charge combustion through in-cylinder direct injection is effective as a means of increasing the fuel economy of spark ignition internal-combustion engines, and automotive manufacturers have developed and marketed direct injection engines in a variety of forms⁽¹⁾⁻⁽³⁾. Honda has continued in this direction with the development of the first 2.0L i-VTEC I direct injection engine. The combustion method employed in this engine uses an original center

injection system to enable the achievement of ultra-lean stratified charge combustion, previously considered difficult in a direct injection gasoline engine, achieving a balance between increased fuel economy and reduced exhaust emissions. The stable supply of a combustible mixture to the area around the spark plug is of the greatest importance to the achievement of stratified charge combustion, and the clarification of the process of formation of the mixture is important in enabling it. This paper will discuss the optimization of the cavity form through analyses of the effect on the mixture formation process generated by changes to parameters such as the fuel spray characteristics and the combustion chamber appropriate to use in a center injection system.

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2. Overview of Engine / Specifications

Table 1 shows the main specifications of the newly developed K20B engine. Figure 1 shows the combustion chamber form. The major issues in achieving ultra-lean stratified charge combustion are ensuring the formation and maintenance of a combustible mixture and fast burn after sparking. The aim established for the new engine was to employ a center injection layout and, by means of the fuel spray characteristics⁽⁴⁾ (Table 1) achieved by the use of a high-penetration injector and the spray flow achieved by a deep-bowl type cavity piston, to stably form and maintain a combustible mixture around the spark plug. A further aim was the achievement of fast burn by means of the swirl generated by the closure of one valve by the VTEC mechanism after sparking. The selection of an appropriate cavity form was very important in realizing this concept. The parameters with the most significant effect on the achievement of stable combustion through enabling the formation of a combustible mixture around the spark plug are the slope angle of the bottom of the cavity, the cavity volume ratio (ratio of cavity volume to total combustion chamber volume), and the deflection angle of the cavity. The research project discussed in this paper sought to define and optimize^{(5),(6)} the parameters of a cavity form enabling the achievement of a high lean combustion limit in stratified charge combustion and a good balance between load and engine speed. Figure 2 shows the form of the piston cavity.

Table 1 Engine specifications

Engine code	K20B
Cylinder configuration	In-line 4-cylinder
Bore × Stroke (mm)	86 × 86
Displacement (cm ³)	1998
Compression ratio	10:1
Valvetrain	DOHC VTEC
Number of valves	4 per cylinder
Fuel injection pressure (MPa)	8 – 10.5
Fuel spray angle (deg)	25
Penetration (mm)	73 (1msec after start of injection)
Fuel spray particle size (μm)	11.4 (Sauter mean diameter) at 10MPa fuel pressure

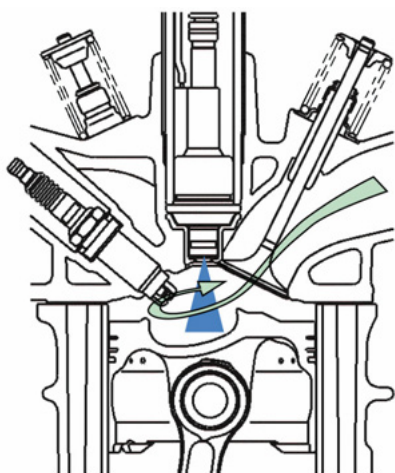


Fig. 1 Combustion chamber configuration

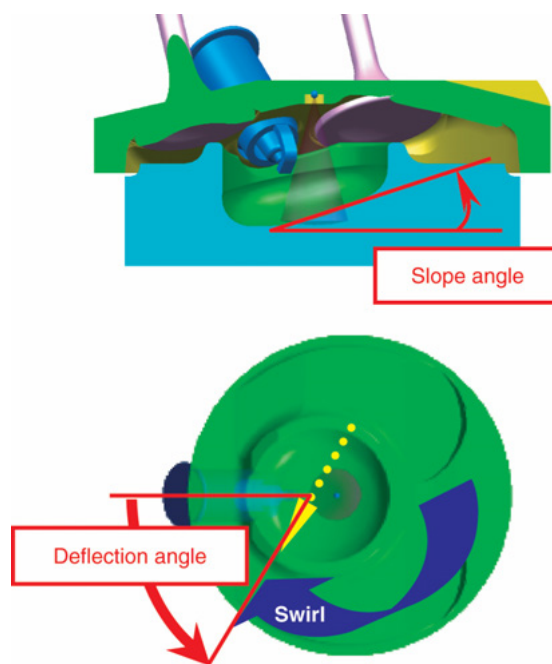


Fig. 2 Form of piston cavity

3. Optimization of Cavity Form

3.1. Visualization of Mixture Distribution and Correlation with Simulation

The large number of parameters in tests with actual equipment made them difficult to employ in defining the required parameters in the optimization of the cavity form. Analyses employing simulations were effective in restricting the parameters. As the first stage of simulation analysis in this project, the results of visualization tests of in-cylinder mixture distribution using LIF were compared and correlated with the results of CFD simulations. Visualization tests employed a single-cylinder engine set up for visualization and observed the in-cylinder mixture distribution at sparking in stratified charge combustion. Figure 3 shows a diagram of the test equipment for LIF visualization. An excimer laser with a 1 mm sheet was employed as the excitation light source, and an image intensifier and CCD camera were used to photograph the fluorescence of a 3-pentanone additive in fuel through the observation window.

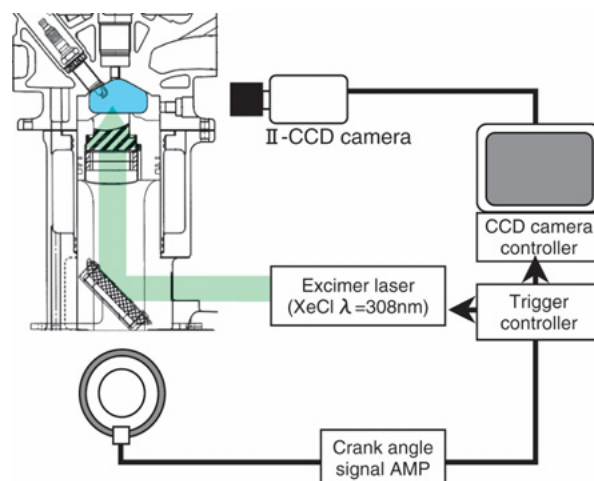


Fig. 3 LIF system for fuel distribution visualization

Figure 4 compares the mixture distribution results for visualization at an engine speed of 1 500 rpm, an indicated mean effective pressures (IMEP) of 267 kPa, and an ignition timing of 40° BTDC with the results of a simulation for the same conditions. The visualization results show that at an injection timing of 40° BTDC, the mixture is most concentrated around the spark plug between 15° and 20° BTDC, and stratified with equivalence ratio of 1.0 or more.

There is a good correlation between the form of the mixture distribution around the spark plug and the extent and density of the distribution of the mixture opposite the spark plug in the results of visualization of compression stroke towards top dead center and the CFD simulation results. The correlation between the visualization, towards top dead center, and CFD simulation demonstrated that simulation could be used as a tool in designing the form of the piston cavity.

3.2. Analysis of In-cylinder Flow and Mixture Distribution

In the next stage of research, simulations were used to analyze the in-cylinder flows and mixture distribution produced by different combustion chamber forms.

3.2.1. Comparison of results for in-cylinder flow

Table 2 shows the cavity volume ratio, slope angle and deflection angle for two different cavity forms, designated type A and B.

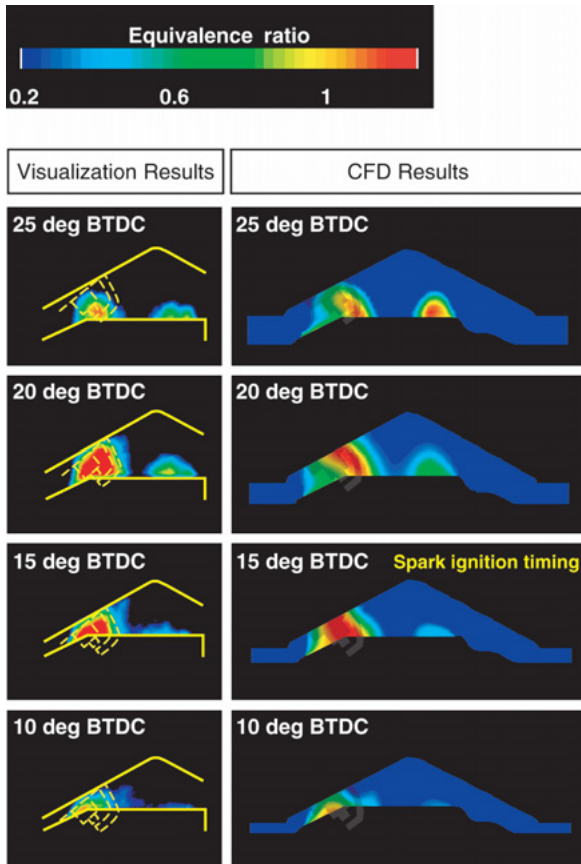
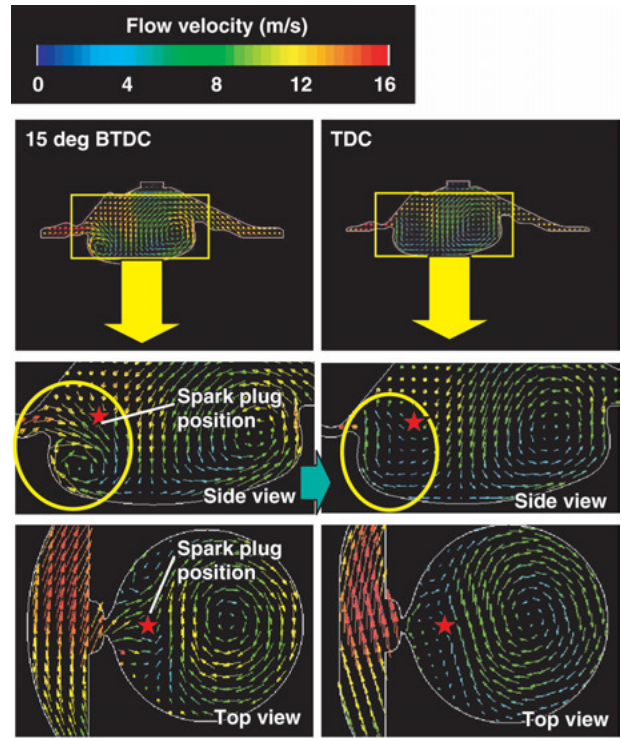


Fig. 4 Comparison of mixture distributions in CFD simulations and measurements

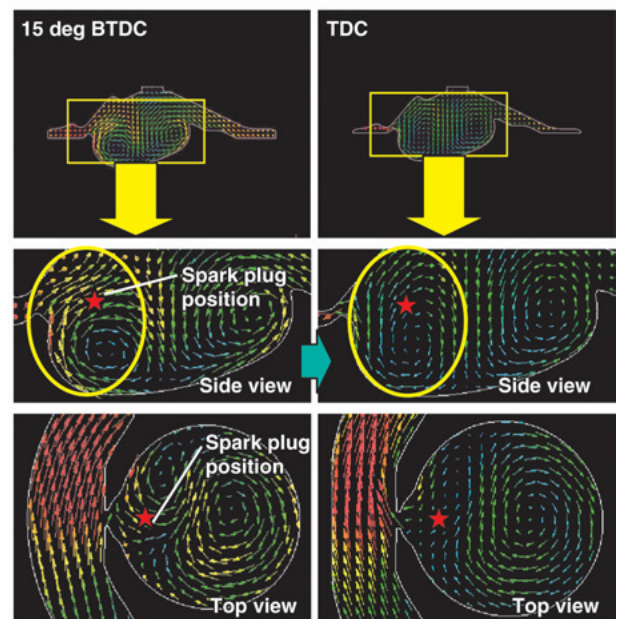
Figure 5 compares simulation results of in-cylinder flow in cavity A and B at 1 500 rpm, an IMEP of 267 kPa and an injection timing of 40° BTDC. The results of a vertical cross-

Table 2 Cavity pattern A, B

Type	Cavity volume ratio (%)	Slope angle (deg)	Deflection angle (deg)
A	28.9	10	60
B	26.4	15	30



(a) Cavity A



(b) Cavity B

Fig. 5 CFD results for flow velocity in piston cavity

section of the combustion chamber show that at 15° BTDC, the vertical vortex forming under the spark plug in cavity B extends further in the vertical direction and has a greater amount of velocity components than the vortex in cavity A. A flow of air from outside the cavity towards the spark position can be observed in cavity A, but this is absent in cavity B. In horizontal cross-section results the direction of the vectors also shows a strong flow from the bottom of the cavity in the direction of the spark plug, and there is no inflow of air towards the inside of the cavity. By contrast, there is an inflow of air from outside the cavity in cavity A. This difference is produced by the strength and size of the vertical vortex forming under the spark plug in the cavities. In cavity B there is no air inflow from outside until top dead center, this enables the formation of a large vortex extending in the direction of the spark plug, and the vortex is maintained until top dead center. This indicates that cavity B enables the stable supply and maintenance of the mixture around the spark plug. In both cavities swirl produced a large vortex, indicating that the swirl flow produced throughout the cylinder by VTEC is transmitted to the cavity and maintained there. This in-cylinder swirl flow could be expected to enable fast burn after sparking.

3.2.2. Comparison of results for mixture distribution

Figure 6 shows a comparison of a simulation of the mixture distribution in cavity A and B at 1 500 rpm, an IMEP of 267 kPa and an injection timing of 40° BTDC. The results for a vertical cross-section of the combustion chamber show that in cavity B at 15° BTDC a stratified mixture with an equivalence ratio of 1.0 or more forms under the spark plug, and the high-density section extends towards the plug. The results obtained in the simulations of in-cylinder flow indicate that this is because the fuel spray is concentrated and carried towards the spark plug by the vertical vortex. In addition, in cavity B the growth of the stratified mixture is maintained until top dead center, and covers a wider area. This is because there is no air inflow into the inside from outside the cavity. In cavity A, the stratified area under the spark plug is divided in two. This phenomenon is generated by the inflow of air into the inside from outside the cavity.

The density of the mixture is also lean. This is because the velocity components of the vertical vortex are small, and do not generate a flow able to concentrate and form the mixture. The results from a horizontal cross-section of the combustion chamber show that in cavity B a mixture with an equivalence ratio corresponding to 1.0 or more formed around the spark plug and was maintained until top dead center. In cavity A the rich mixture was concentrated more on the upstream of the swirl than the spark position, and only a lean mixture was present around the spark plug. This is because the flow of air from outside the cavity limited the advance of the combustible mixture to the area around the spark plug. The results of these simulations showed that the deflection angle of the cavity has an effect on the size and strength of the vertical vortex, and the cavity volume ratio has an effect on the concentration of the mixture. The results also show that in cavity B a very rich mixture is present around the spark plug, and the mixture is maintained well.

Figure 7 shows a comparison of the lean combustion limit for cavity A and B against amount of restriction of the throttle under the same load in DISC operation at 1 500 rpm. Opening the throttle and increasing the volume of air throughout the cylinder does not cause any rapid increase in indicated specific fuel consumption (ISFC) or variation of combustion in cavity B, and they remain stable up to an air-

fuel ratio of around 80. This demonstrates that the stratification and maintenance of a combustible mixture is possible in the cavity despite the high volume of air flowing into the cylinder when the throttle is opened. By contrast, in cavity A, ISFC reaches its minimum at an intake manifold pressure of -20 kPa, and there are rapid increases in ISFC and variation of combustion as the throttle is opened. This indicates that mixture cannot be maintained in the cavity, and mixture around the spark plug is made lean by air inflow into

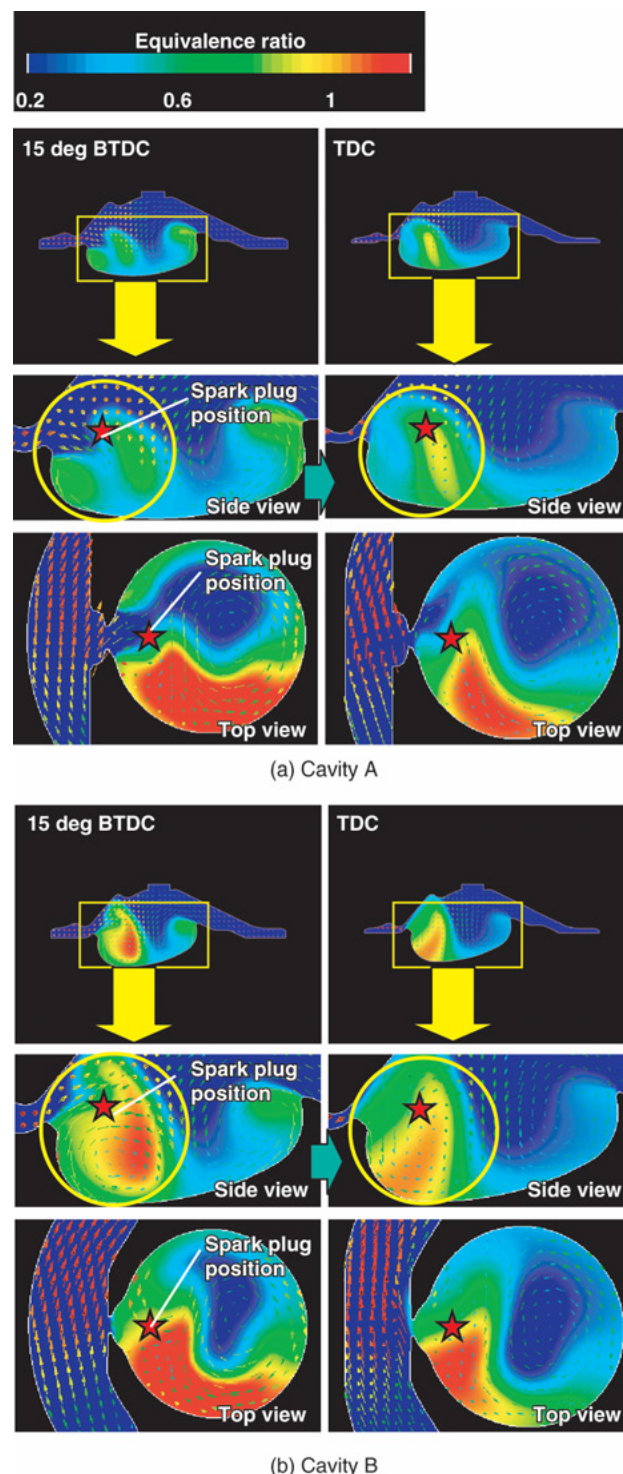


Fig. 6 CFD results for stratified mixture formation in piston cavity

the cavity. In addition, there are significant differences between the absolute values of ISFC, air-fuel ratio and variation of combustion in cavity A and B at identical intake manifold pressures. These results corresponded well with the results of simulations showing the effect of the presence or absence of a flow of air into the cavity due to the strength of the vertical vortex on in-cylinder flow and the mixture distribution.

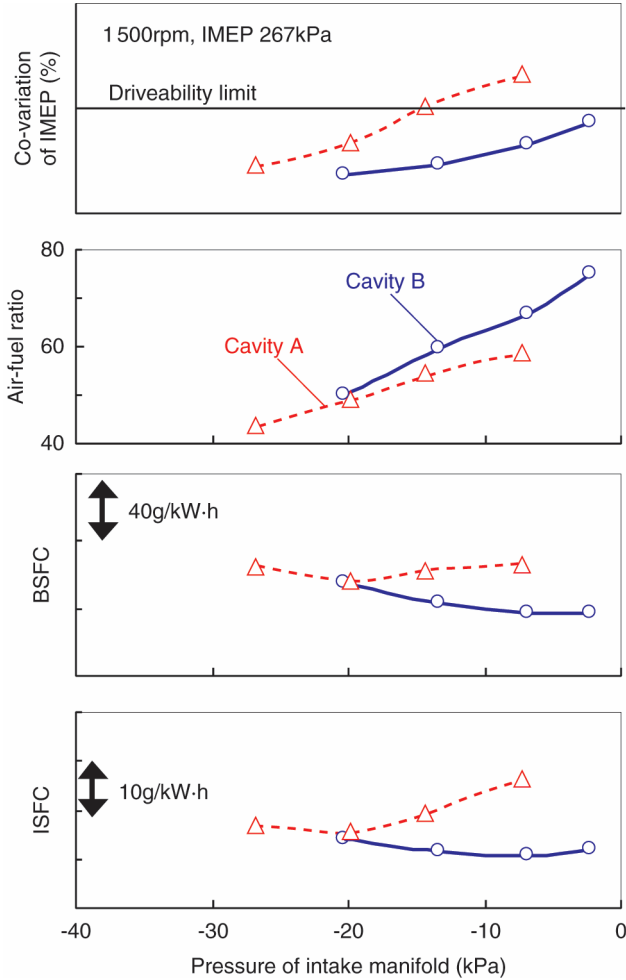


Fig. 7 Influence of pressure of intake manifold on combustion characteristics and lean combustion limit

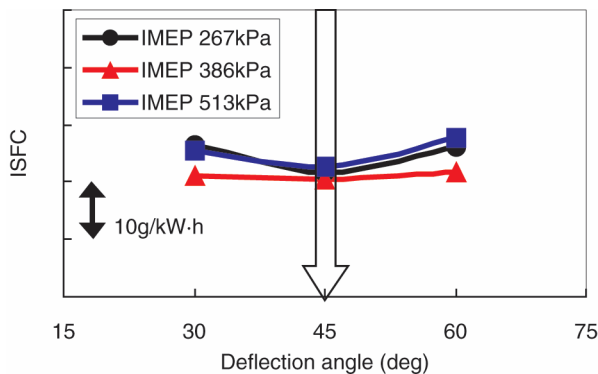


Fig. 8 Influence of deflection angle on ISFC

The results of analyses of the mixture using simulations and of measurements of lean combustion limit in engine tests described above showed that cavity B enabled the formation of a mixture with a higher lean combustion limit than cavity A, would significantly reduce BSFC by reducing pumping loss, and also demonstrated little variation of combustion.

The slope angle and volume ratio of cavity B were therefore adopted as the specifications of the new cavity, while performance tests were carried out using different deflection angles to optimize this parameter. Figure 8 shows ISFC for different deflection angles at an engine speed of 1 500 rpm and IMEP of 267, 386 and 513 kPa.

The effect of the difference in deflection angles was apparent at low loads and high loads. A deflection angle of 45° was judged most suitable in terms of swirl strength, and produced the best results for ISFC. This resulted in the adoption of the cavity specifications shown in Table 3.

Table 3 Optimized cavity specifications

Cavity volume ratio (%)	Slope angle (deg)	Deflection angle (deg)
26.4	15	45

4. Air-fuel Ratio Around Spark Plug

Infrared absorption method was used to conduct measurements of the air-fuel ratio around the spark plug during stratified charge combustion for the optimized cavity form^{(7),(8)}, enabling the process of mixture formation and its level of stability to be studied. Figure 9 shows the setup of the measurement equipment. Infrared light with a wavelength of 3.392 μm generated by a He-Ne laser was directed by optic fiber to the measurement area at the spark plug. Having passed the measurement area, where it was absorbed and attenuated by the gasoline, the light was directed by another optic fiber to the detection area, where its transmissivity was measured. Figure 10 shows the configuration of the measuring probe.

Measurements were conducted under conditions of an engine speed of 1 500 rpm, an IMEP of 270 kPa, a mean air-fuel ratio of 45 and a fixed ignition timing of 15° BTDC. Figure 11 shows average results over 100 cycles for air-fuel

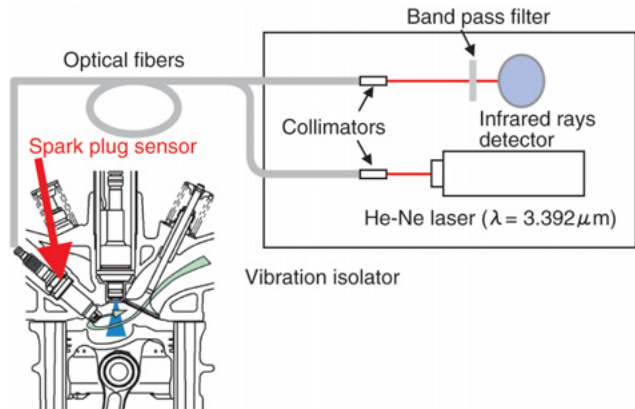


Fig. 9 Experimental setup for concentration measurement in direct injection engine

ratio around the spark plug and their standard deviation for injection timings of 30°, 40° and 50° BTDC. For all the injection timings, the air-fuel ratio at the spark plug was stoichiometric at approximately 20° after the end of injection, after which it became richer until it reached a figure of around 10, and the mixture was maintained at this air-fuel ratio for a specific period of time. With respect to the air-fuel ratio around the spark plug at ignition timing, a combustible mixture did not form around the spark plug with an injection timing of 30°, but there was no significant difference observed for timings of 40° and 50°, with ratios of around 10 for each. Figure 12 shows the variation of air-fuel ratio and combustion at ignition timings. A correlation can be observed between variation of air-fuel ratio and combustion at ignition timing, with air-fuel ratio most stable and the minimum variation of combustion at a timing of 40°. Figure 13 shows the relationship between the air-fuel ratio around the spark plug at ignition timing and ignition delay (the period from sparking to a mass fraction burned of 10%). Here also an injection timing of 40° shows the least ignition delay and the most rapid combustion, and this timing was therefore adopted as optimum.

Figure 14 shows the effect of different injection timings on combustion in engine tests at identical engine speeds and loads. The optimum ignition timing to minimize ISFC was employed in each case. These results show that the employment of a piston cavity form ensuring a high level of maintainability of the mixture and a center injection system have enabled the achievement of stable combustion across a broad range of injection timings from 20° to 50° BTDC. ISFC is at its minimum between 40° and 50°, and the results of performance tests have indicated that 40° is the optimum timing from the perspective of NO_x and HC emissions and variation of combustion. Infrared absorption method and performance tests have indicated that the piston cavity specifications developed in this research have realized initially established aims for mixture formation, and enable the achievement of a high lean combustion limit and significantly improved fuel economy.

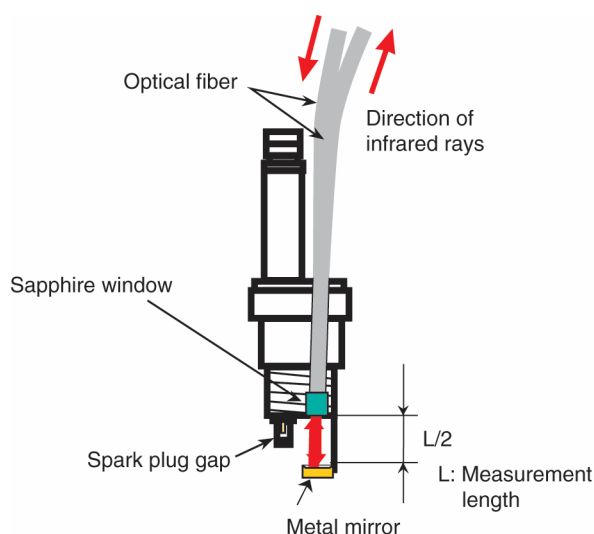


Fig. 10 Schematic of measuring probe

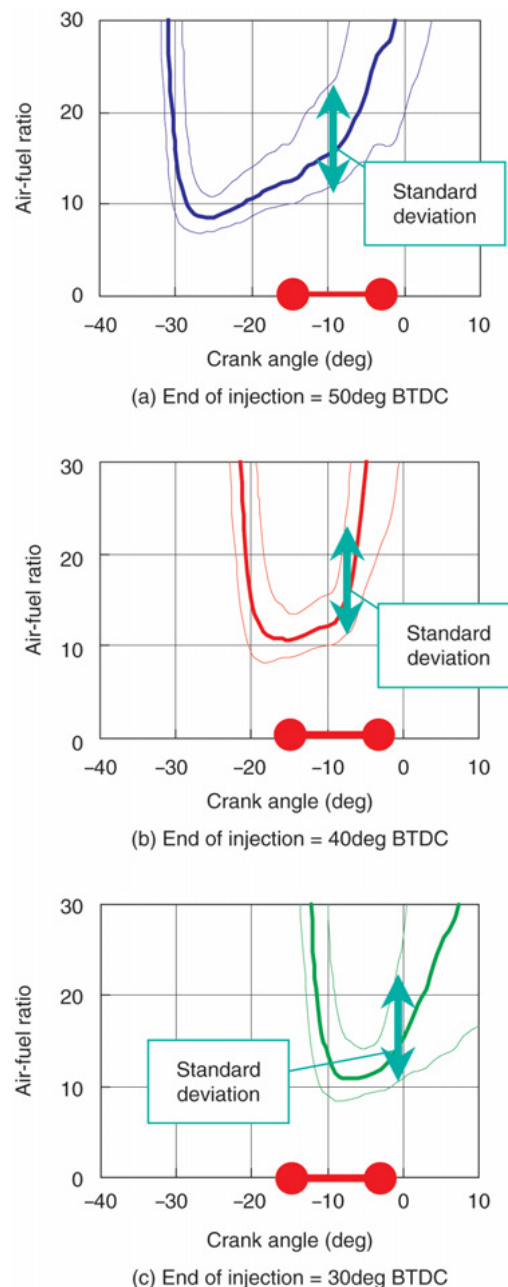


Fig. 11 Air-fuel ratio at spark plug

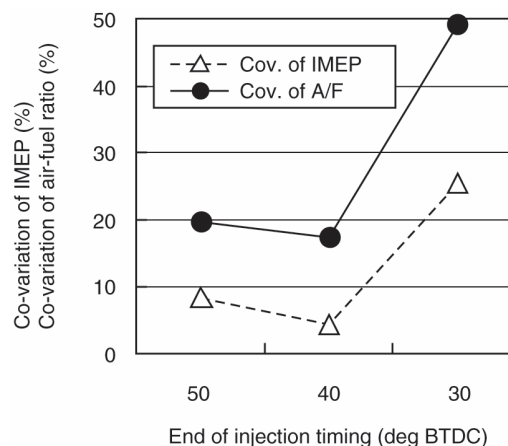


Fig. 12 Influence of injection timing on coefficient of variation in air-fuel ratio at spark plug and coefficient of variation in IMEP

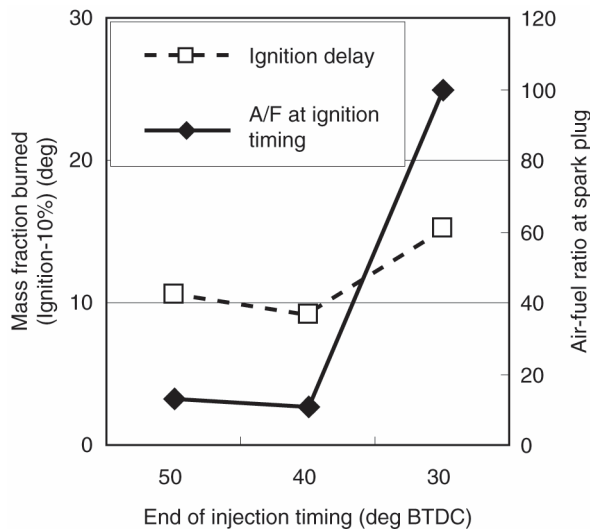


Fig. 13 Influence of injection timing on air-fuel ratio at spark plug and ignition delay

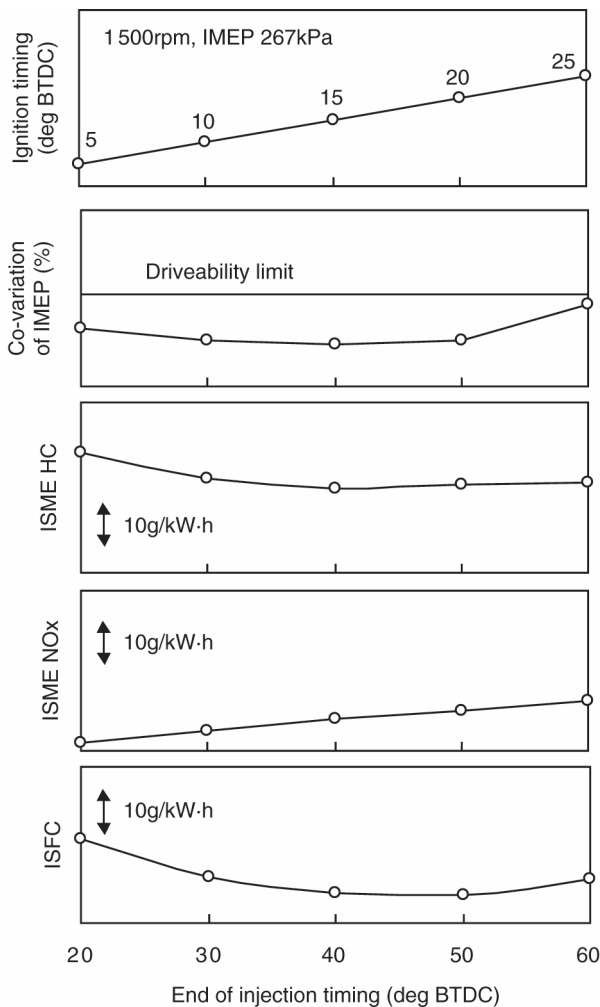


Fig. 14 Influence of injection timing on combustion characteristics

5. Conclusion

Analyses of in-cylinder flow and mixture distribution, infrared absorption method of the air-fuel ratio around the spark plug and the results of engine tests conducted to enable the optimization of the form of the piston cavity have produced the following conclusions:

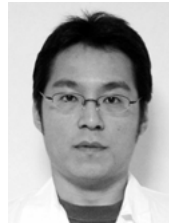
- (1) Optimization of the slope angle, volume ratio and deflection angle of the piston cavity has enabled the generation of a strong vertical vortex in the cavity by a center injection system with a high-penetration spray, resulting in excellent concentration and maintenance of the mixture around the spark plug.
- (2) The optimized cavity records its best figures for ISFC at an air-fuel ratio of around 70 and has a high lean combustion limit, with variations of combustion remaining within the range allowing stable combustion up to an air-fuel ratio of 80, resulting in significant reduction of BSFC.
- (3) CFD simulations showed that differences in cavity specifications produced differences in in-cylinder flow and mixture distribution, and correlated well with the results of engine tests.
- (4) Infrared absorption method of air-fuel ratio around the spark plug and the results of performance tests showed that the optimized cavity specification enabled rapid stratification and stable maintenance of the mixture around the spark plug, and enabled stable combustion for a wide range of injection timings.

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