

Development of High-performance and Low-emission Direct Injection Gasoline Engine

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ABSTRACT

Honda has developed the first-ever 2.0L i-VTEC I direct injection gasoline engine employing a center injection system in which a high-pressure fuel injector is located in the center of the combustion chamber. This engine significantly improved fuel economy and emissions performance. Optimization of in-chamber fuel flow through a redesign of piston shape, the spray characteristics of the high-pressure fuel injector, and the application of VTEC has enabled the achievement of stable combustion of a stratified ultra-lean air-fuel mixture. Due to the VTEC mechanism and the continuous variation of the camshaft phase enabled by VTC, the engine has achieved top-class power for a high fuel economy engine. The new engine is fitted in the 2004 Stream that, in combination with the CVT employed in the vehicle, has enabled the Stream to achieve a low fuel consumption figure of 15.0 km/l in Japanese 10 - 15 mode. A large amount of EGR and a high-performance lean NOx catalyst to reduce emissions has further enabled the Stream to become the first vehicle with an engine employing ultra-lean stratified charge combustion to achieve an emissions level of only 25% of the level stipulated by the Japanese 2000 emissions regulations and obtain Ultra Low Emission Vehicle (ULEV) certification.

1. Introduction

The automotive industry has progressed with the development of power plants with a focus on the achievement of high fuel economy and low emissions. This focus has been in response to increasing concern towards the global environment. In particular, a variety of direct in-cylinder fuel injection gasoline engines have been developed, given the efficacy of direct injection in increasing the fuel efficiency of spark ignition internal combustion engines^{(1), (2)}. Honda has also responded to the challenge by putting its next-generation power plant, the i-series^{(3), (4)}, into production. In a further development, the 2.0L i-VTEC lean-burn engine developed for the 2000 model Stream⁽³⁾ has been used as a base in the development of the world's first 2.0L i-

VTEC I direct injection gasoline engine. An original concept of center direct injection was employed in the new engine to enable the achievement of ultra-lean stratified charge combustion in order to improve fuel economy and reduce emissions. This paper discusses the technologies employed to achieve ultra-lean combustion in the 2.0L i-VTEC I direct injection engine, which was previously considered a challenging issue in a direct injection gasoline engine.

2. Development Goals

The development concept for the new model Stream, in which this engine is installed, was to achieve a balance between superior environmental performance and sportiness.

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A CVT is employed to take the significant gains in fuel efficiency achieved through the use of a direct injection engine to an even higher level. The increased power of the direct injection engine and the optimization of the ratio through the use of CVT would enable the achievement of both excellent dynamic performance and a high level of environmental performance. The specific targets of the development were as follows:

- (1) High fuel economy (10 - 15 mode: 15.0 km/l)
- (2) Low emissions (Ultra low emissions level – Reduction of emissions level by 75% against values stipulated by 2000 regulations)
- (3) High power for sporty performance

3. Overview of Engine / Specifications

Figure 1 shows an external view of the engine, and Table 1 shows a comparison of the specifications of the newly developed K20B engine and the previous K20A engine. The effectiveness of direct in-cylinder fuel injection in increasing intake air charging efficiency and suppressing knocking is well known^{(5), (6)}. The most distinctive feature of the new engine is the employment of a center injection system, which makes use of these characteristics of direct injection to achieve ultra-lean stratified charge combustion. This application results in significant improvements in fuel economy, emission performance, and increased power. Figure 2 (a) shows the positioning of the high-pressure fuel injector in the center of the combustion chamber, and Fig. 2 (b) shows the positioning of the spark plug between the exhaust valves. To reduce the space required for this configuration, the diameters of the inlet and exhaust valves have been reduced by 1 and 2 mm respectively compared to the previous model. Optimization of the valve lift profile and the shape of the inlet and exhaust ports has ensured that intake and exhaust efficiency is equivalent or superior to that demonstrated by the previous model, despite the reduction in the diameter of the valves.

In the valve system, VTEC and cam shaft phase continuation variable timing control (VTC) have been employed to balance ultra-lean stratified charge combustion with high power. The higher compression ratio and redesigned intake and exhaust layout of the K20B give it increased torque in the medium- to high-speed range compared to the previous K20A engine. This results in improved fuel economy and running performance. Figure 3 shows the power characteristic of both engines with the throttle fully open.



Fig. 1 K20B direct injection gasoline engine

Table 1 Engine specifications

Engine Code	K20B	K20A
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	86 × 86	86 × 86
Displacement (cm ³)	1 998	1 998
Compression ratio	10:1	9.8:1
Valve train	DOHC VTEC	DOHC VTEC
Number of valves	4 per cylinder	4 per cylinder
Valve diameter (mm)	In. 34	35
	Ex. 28	30
Fuel supply system	Programmed fuel injection	Programmed fuel injection
Fuel injection pressure (MPa)	8 - 10.5	0.34
Ignition system	Programmed ignition	Programmed ignition
Max. power (kW/rpm)	115 / 6300	113 / 6500
Max. torque (N·m/rpm)	188 / 4600	186 / 4000

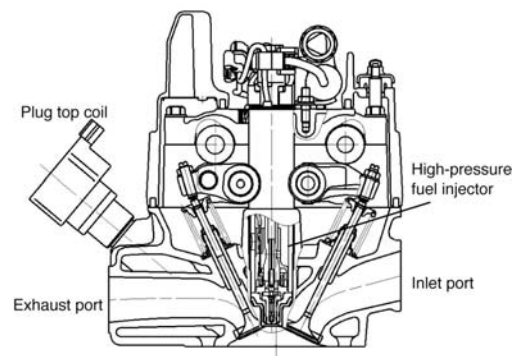


Fig. 2 (a) Section view of cylinder head

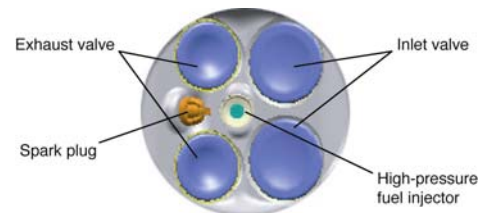


Fig. 2 (b) Configuration of cylinder head

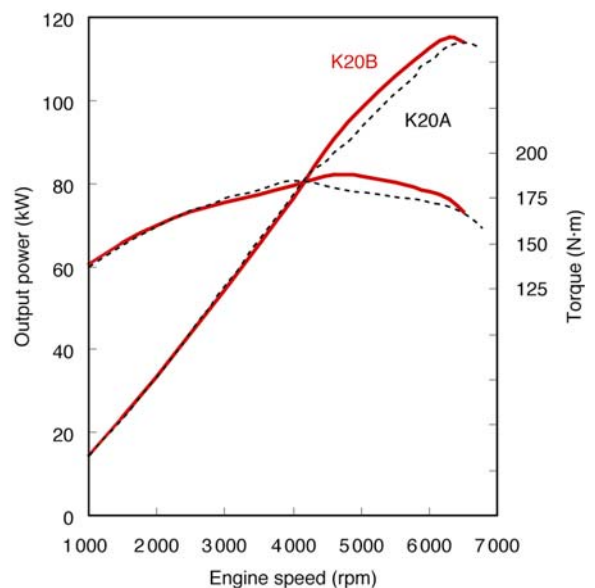


Fig. 3 Engine performance

Figure 4 shows the high-pressure fuel injector and the high-pressure fuel pump that utilizes a single plunger driven by the exhaust cam. Figure 5 shows the spray characteristics of the high-pressure fuel injector. The fuel pressure is controlled within a high range between 8 and 10.5 MPa depending on driving conditions. The pressurized fuel is converted to atomized droplets by the swirl guide channel in the injector before being injected into the cylinder. Atomization brings the diameter of the droplets in the spray to less than $SMD12\ \mu m$. The spray characteristic is set for high penetration at an oblique angle to increase the ability to maintain the air-fuel mixture.

4. Combustion Concept

The achievement of ultra-lean stratified charge combustion requires the formation and maintenance of a combustible air-fuel mixture and rapid combustion after sparking. The least amount of in-cylinder intake air flow is desirable to form and maintain the air-fuel mixture. On the other hand, it is desirable for in-cylinder flow and turbulence to be stronger to achieve rapid combustion of the air-fuel mixture after sparking in order to increase thermal efficiency. The concept proposed to balance these antagonistic demands was to form and maintain the air-fuel mixture by spray flow using a high-penetration fuel injector positioned in the center of the cylinder and a cavity piston, and to employ the swirl produced by the closure of one valve by the VTEC mechanism to achieve rapid combustion (Fig. 6).

When high power is demanded from the engine, the VTEC mechanism switches to operation of both inlet valves to increase volumetric efficiency, fuel is supplied into the intake stroke, and combustion becomes homogeneous at a stoichiometric air-fuel ratio. This configuration gives the engine high power and high responsiveness. Given that no fuel adheres to the wall of the cylinder in the combustion chamber in this system, it reduces the level of unburned HC compared to the former side injection system. Figure 7 shows the range of each combustion mode in the K20B engine. The figure demonstrates the high degree of freedom of fuel injection timing and the broad stratified charge combustion range achieved by this system.

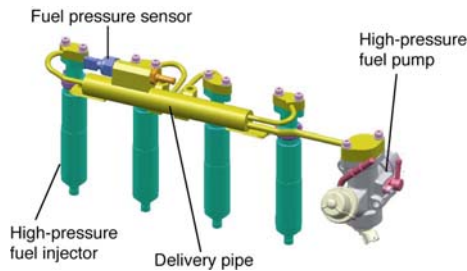


Fig. 4 High pressure fuel system

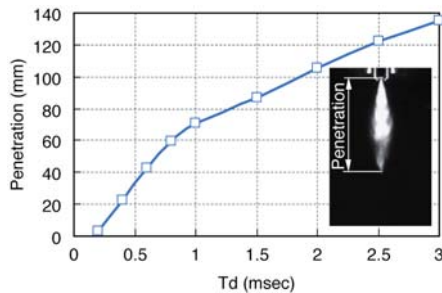


Fig. 5 High-pressure injector spray characteristics

4.1. Shape of Piston Cavity

Figures 8 (a) and 8 (b) show external views of the piston. The cavity piston is positioned so that the bottom of the cavity has a slope angle to the spark plug, and the cavity is deeper on the spark plug side. The deepest part of the cavity is deflected towards the upstream side of the swirl. This enables the swirl of air-fuel mixture to be formed in the cavity by the high-speed spray from the injector, maintained,

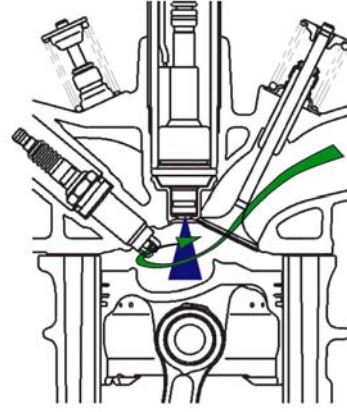


Fig. 6 Combustion chamber configuration

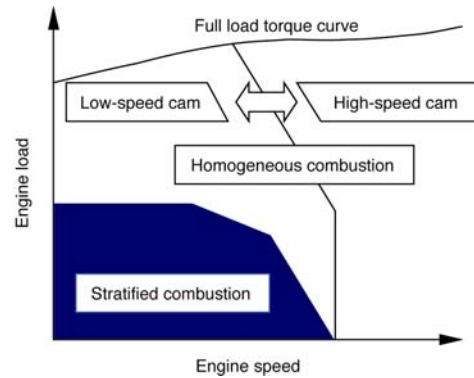


Fig. 7 Map of combustion mode

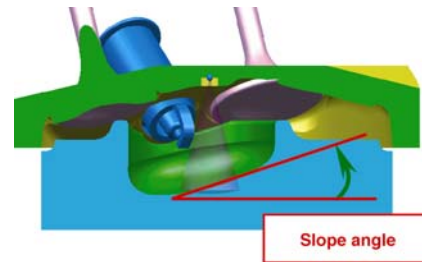


Fig. 8 (a) Section view of piston

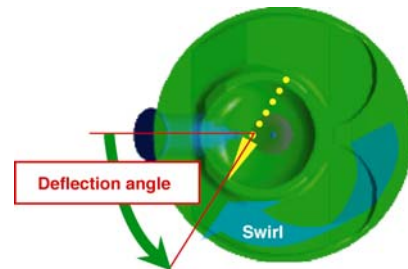


Fig. 8 (b) Top view of piston

and carried by the swirl flow to the spark plug. The volume of the cavity and the angles of slope and deflection were optimized by actual engine tests, visualization of air-fuel mixture in the combustion chamber, and simulations of air-fuel mixture distribution.

4.1.1. Establishing cavity specifications

Figure 9 shows the indicated specific fuel consumption (ISFC) characteristic with changes in the cavity volume ratio (ratio of cavity volume to total combustion chamber volume) during stratified combustion. As the cavity volume decreases, ISFC at low loads improves and stratification increases. But, at high loads, the air-fuel mixture in the cavity tends to become over-rich, with a negative effect on ISFC. A cavity volume ratio of 26% was established for the new engine to produce an optimum balance of stratified charge combustion across all engine loads.

The influence of the slope angle of the bottom of the cavity on ISFC is shown in Fig. 10, and the influence of the deflection angle in Fig. 11.

When the slope angle of the bottom of the cavity is low, the air-fuel mixture is not strongly directed to the spark plug. This has a negative effect on ISFC at low loads when the amount of fuel injected is low. The optimum value for the deflection angle of the cavity varies with the strength of the swirl in the cylinder. An angle of slope of 15° and an angle of deflection of 45° were established for the K20B.

4.1.2. Distribution of air-fuel mixture

Figure 12 shows the simulation results of the distribution of the air-fuel mixture and air motion during stratified charge combustion. The spray injected into the cylinder during the compression stroke follows the slope of the bottom of the cavity and is guided to the deepest part of the cavity, which deviates towards the upstream of the swirl. The high spray penetration achieved by high-pressure injection creates vertical vortexes from the walls towards the center of the cylinder. These vertical vortexes prevent the dispersion of the air-fuel mixture and increases maintainability, forming a compact agglomeration of the mixture.

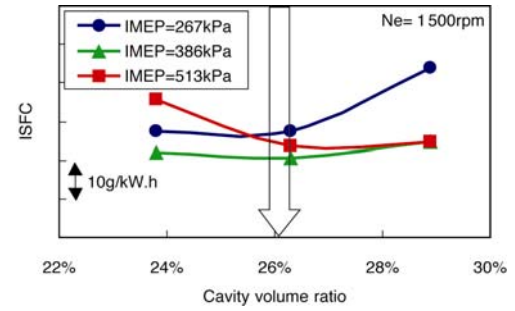


Fig. 9 Influence of cavity volume ratio on ISFC

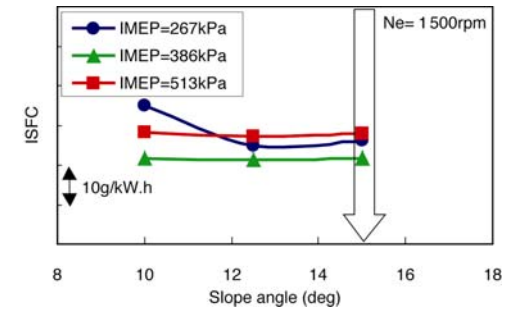


Fig. 10 Influence of slope angle on ISFC

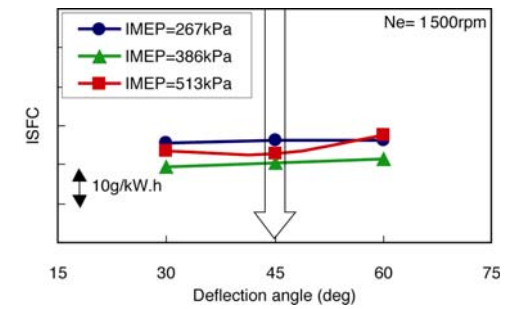


Fig. 11 Influence of deflection angle on ISFC

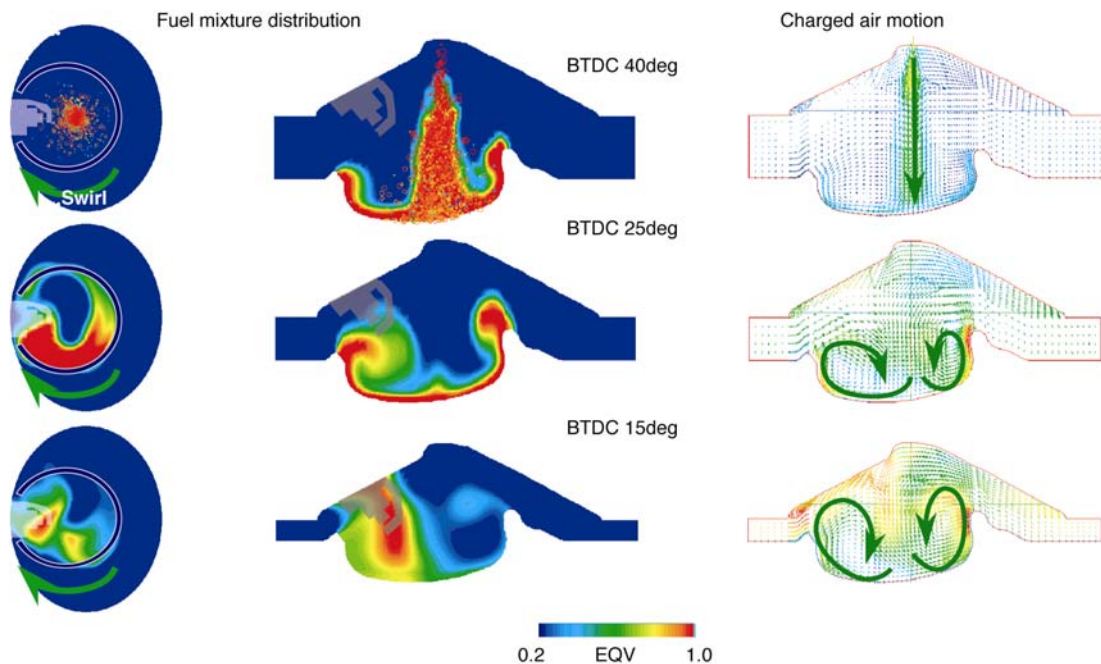


Fig. 12 Simulation of fuel mixing process and air motion in stratified charge combustion

After colliding with the piston cavity, the gasified air-fuel mixture is carried in the direction of the spark plug by the in-cylinder swirl. A stable, combustible mixture is therefore present around the spark plug at the spark timing of BTDC 15°, ensuring stable combustion in the ultra-lean stratified charge combustion range.

4.2. Combustion Characteristics

Figure 13 shows data from analyses of ISFC, HC and NO_x emissions and in-cylinder pressure against injection timing with the engine in DISC mode at 1 500 rpm.

The employment of a piston cavity shape ensuring high maintainability of the mixture and the use of center injection have enabled the achievement of stable combustion at a broad range of injection timings, from BTDC 20° to 50°. The optimum injection timing for this load in terms of fuel consumption, emissions and combustion stability is BTDC 40°. If injection timing is advanced to BTDC 60°, the mixture disperses, stratification is reduced, and combustion fluctuates. By contrast, if injection timing is retarded to around BTDC 20°, fuel efficiency is reduced. The increased HC emissions at this injection timing indicate that this is caused by an increase in the amount of afterburn, lengthening the time required for combustion and thus increasing ISFC. There are therefore injection timings at which ISFC in the DISC area reaches its lowest level. Injection timings in the K20B have been optimized to enable the achievement of an excellent balance between ISFC and emissions levels at different engine speeds and loads.

Figure 14 shows data for brake specific fuel consumption (BSFC), NO_x emissions, air-fuel ratio and in-cylinder pressure against EGR rate with ultra-lean stratified

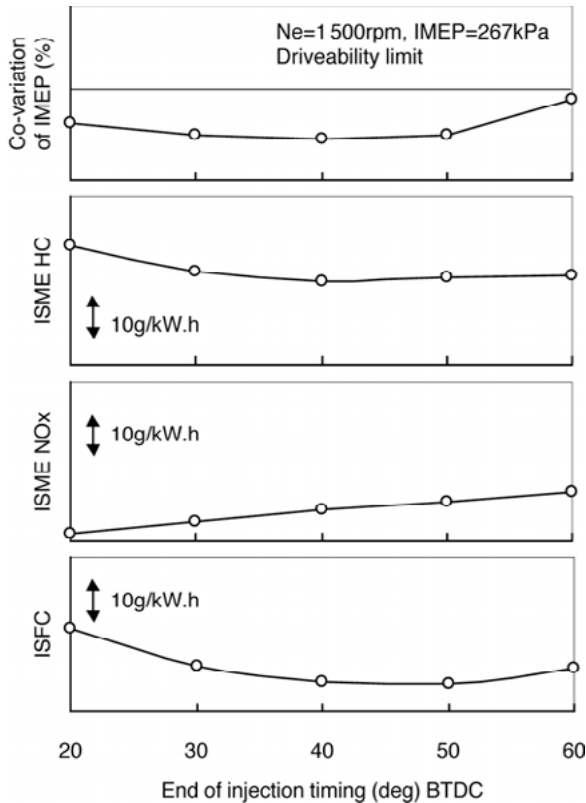


Fig. 13 Influence of injection timing on combustion characteristics

charge combustion at an engine speed of 1 500 rpm. Combustion is stable even at an EGR rate of 40%, at which BSFC is at its lowest level. In addition, mass EGR has reduced feed NO_x by approximately 80%.

Figure 15 shows the results of analyses of in-cylinder pressures for DISC and stoichiometric combustion at Ne = 1 500 rpm and BMEP = 118 kPa. The stratification of the air-fuel mixture in the piston cavity during DISC reduces sparking delay compared to the homogeneous combustion occurring at stoichiometric air-fuel ratios. In addition, combustion is initiated more quickly after sparking, resulting in rapid combustion. This rapid combustion has been enabled by the employment of an atomized high-penetration spray and a piston cavity which maximizes maintainability to form the air-fuel mixture and the generation of an in-cylinder swirl flow.

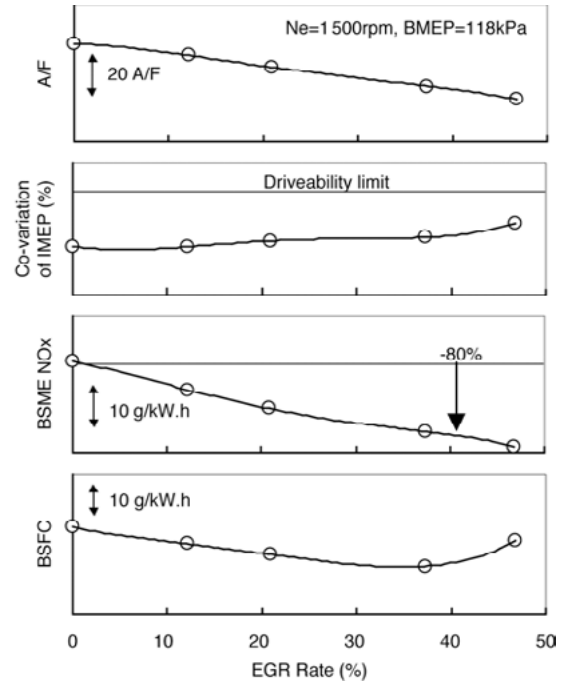


Fig. 14 BSFC, NO_x combustion characteristics

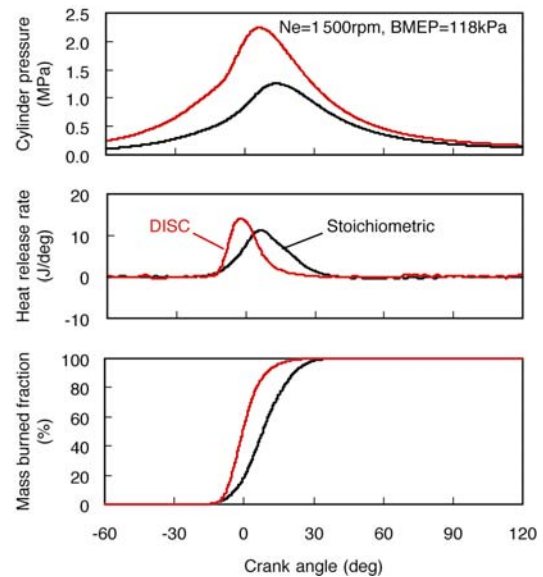


Fig. 15 Comparison of combustion characteristics

5. Engine Unit Fuel Efficiency and Vehicle Fuel Efficiency

5.1. Engine Unit Fuel Efficiency

Figure 16 shows the relationship between total engine displacement and BSFC. The reduction of heat loss and pumping loss and the increase in specific heat ratio achieved through ultra-lean stratified charge combustion in the direct injection engine has reduced BSFC by 20% against a conventional stoichiometric air-fuel ratio combustion engine.

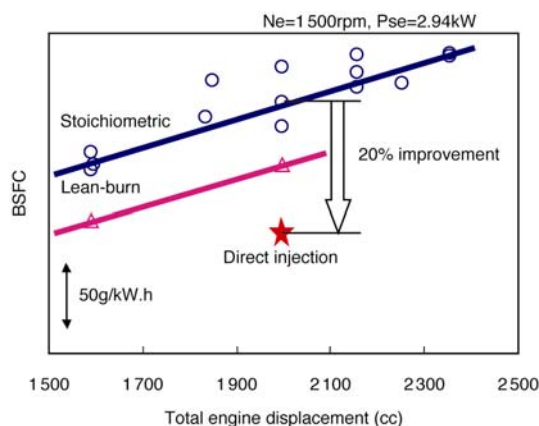


Fig. 16 Improvement of BSFC

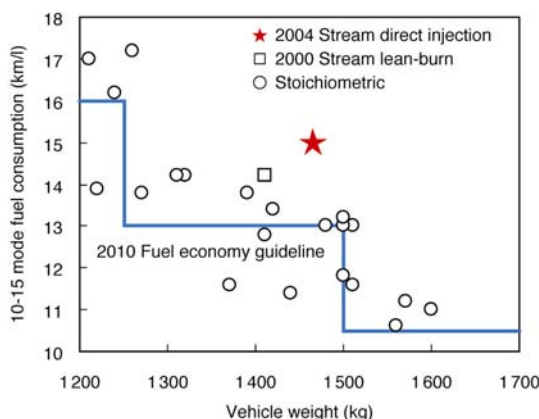


Fig. 17 Relationship between vehicle weight and 10 - 15 mode fuel economy in production gasoline vehicles

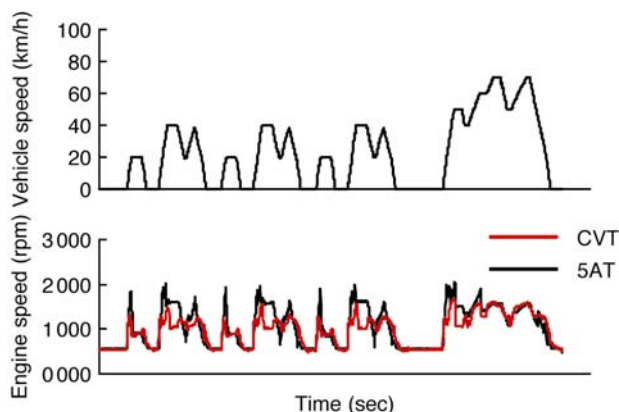


Fig. 18 Comparison of 10 - 15 mode engine speed between CVT and 5AT

5.2. Vehicle Fuel Efficiency

Figure 17 shows the relationship between vehicle weight and fuel consumption in Japanese 10 - 15 mode. Figure 18 compares engine speed in 10 - 15 mode in vehicles fitted with a CVT and a 5AT. Cooperative control of the engine and CVT is set to hold the engine operating range at low speeds, and therefore the engine operates at low BSFC. In 10 - 15 mode, the vehicle fitted with a CVT is able to cruise and accelerate at lower engine speeds than the vehicle fitted with a 5AT.

The improved fuel economy achieved through ultra-lean stratified charge combustion and the application of cooperative control with the CVT has enabled the reduction of fuel consumption. The resulting fuel economy in the 10 - 15 mode has been reduced by approximately 15% compared to the vehicle with a stoichiometric engine, achieving a low fuel consumption of 15.0 km/l. This is excellent fuel consumption performance, well below the standards established in the 2010 fuel consumption regulations.

6. Emissions Control Technology

Stratified charge combustion had never previously been employed in a direct injection engine. The emissions control system for the new engine was developed with the target of reducing emissions in a direct injection engine by 75% against the values stipulated in 2000 regulations, which meets the J-ULEV. Development proceeded with a major focus on reducing feed gases in the lean area and increasing the NOx purification rate.

6.1. Exhaust System

The exhaust system of the new engine is shown in Fig. 19. A 4-1 system with a rear exhaust was adopted to balance high power and purification performance. The catalyst and sensor configuration was selected to enable purification during a cold start at a stoichiometric air-fuel

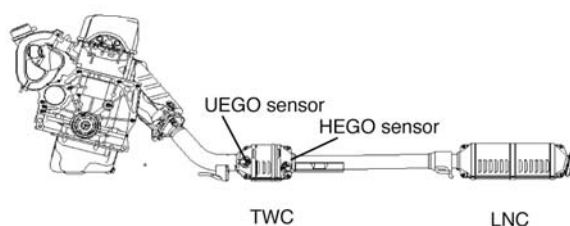


Fig. 19 Configuration of exhaust system

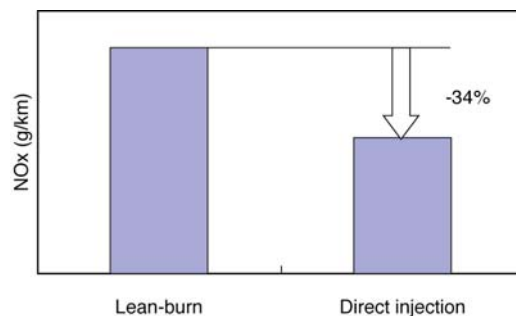


Fig. 20 Comparison of feed NOx emission in 10 - 15 mode between lean-burn engine and direct injection engine

ratio and HC purification during lean operation. A universal exhaust gas oxygen (UEGO) sensor was positioned upstream of the three-way catalyst (TWC), and a heated exhaust gas oxygen (HEGO) sensor was positioned downstream, to ensure high-accuracy control of air-fuel ratio. In addition, a NO_x adsorption reduction-type TWC was positioned under the floor to enable NO_x purification when the engine operates in the lean area.

6.2. Achieved Emissions Values

Figure 20 shows a comparison of the feed NO_x level in the lean area in conventional lean-burn combustion and ultra-lean stratified charge combustion. The possibility of employing mass EGR during ultra-lean stratified charge combustion in the new engine has resulted in a 34% reduction in feed gases in the 10 - 15 mode.

Figure 21 shows the purification characteristics of the lean NO_x catalyst by differences in concentration of NO_x in exhaust gas. The lower the concentration of NO_x in the feed gases, the higher the purification rate of the lean NO_x catalyst. The mass EGR achieved with ultra-lean stratified charge combustion in the direct injection engine has enabled a reduction in the concentration of NO_x. Also, improvements to the lean NO_x catalyst have enabled it to control NO_x to a lower volume than the lean NO_x catalyst employed in the 2000 model lean-burn engine (Table 2).

Control for switching from ultra-lean stratified charge combustion to stoichiometric combustion has been optimized. This enables the vehicle to achieve both a high fuel economy of 15.0 km/l in Japanese 10 - 15 mode and to reduce emissions by 75% against the values stipulated in 2000 regulations, leading to the vehicle receiving ULEV Certification.

7. Conclusion

The i-VTEC I direct injection gasoline engine has the following technological characteristics:

- (1) Ultra-lean stratified charge combustion has been achieved by the employment of a center injection system, an original cavity piston, and the formation of the air-fuel mixture using the in-cylinder swirl produced by VTEC.
- (2) The vehicle has a top-class fuel economy of 15.0 km/l in 10 - 15 mode.
- (3) The employment of a stratified charge combustion

Table 2 Catalytic converter specifications

	2004 Model direct injection	2000 Model lean-burn
TWC	1.0L 600cell	0.7L 400cell
LNC	1.4L 400cell Improved	2.4L 400cell Adsorption type

control system using mass EGR and a high-performance lean NO_x catalyst in an engine that switches from stratified to homogeneous combustion has enabled the reduction of emissions by 75% against 2000 regulation values, which lead to ULEV certification.

References

- (1) Ashizawa, T., Saitoh, K., Tamura, Y., Sakai, T.: Development of a New In-line 4-cylinder Direct-Injection Gasoline Engine, JSAE Annual Congress Proceedings, No. 71-98, JSAE9838237
- (2) Norota, K., Harada, J., Abe, S., Yoshioka, Y., Aoyama, K.: Development of a New L-4 Direct Injection SI Gasoline Engine, JSAE Annual Congress Proceedings, No. 78-00, JSAE20005525
- (3) Niizato, T., Hayashi, A.: Development of New 2.0L Lean-burn Engine, HONDA R&D Technical Review, Vol. 12 No. 2, p. 45-54 (2000)
- (4) Nakayama, Y., Suzuki, M., Iwata, Y., Yamano, J.: Development of a 1.3L 2PLUG Engine for the 2002 year Model Fit, Honda R&D Technical Review, Vol. 13, No. 2, p. 43-52 (2001)
- (5) Kuma, T., Iwamoto, Y., Iida, K., Murakami, M., Akishino, K., Ando, H.: Combustion Control Technologies for Direct Injection SI Engine, SAE Paper 960600
- (6) Okamoto, K., Ichikawa, T., Saitoh, K., Oyama, K., Hiraya, K., Urushihara, T.: Study on Relationship between Octane number and anti-knock performance in Direct Injection Spark Ignition Gasoline Engine, SAE Annual Congress Proceedings, No. 73-02, JSAE20025175

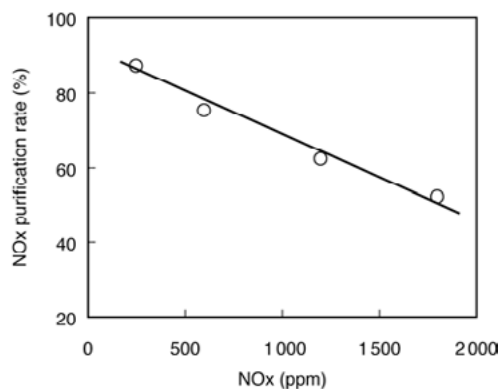


Fig. 21 NO_x purification characteristics

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