

Development of New Turbocharged Common Rail Diesel Engine

Tomoya ABE*

Kenichi NAGAIRO*

Yoshihito TSUJI*

Kiyoshi TSUKIMURA*

Hirokazu OHSAKI*

Kazunori OZAWA*

ABSTRACT

Honda has developed its first 2.2L 4-cylinder diesel engine for the 2004 model Accord being marketed in Europe.

The newly developed engine has a number of distinctive features. The employment of the latest 1 600 bar common rail control system, an EGR cooler and an after-treatment system has enabled the engine to comply with the EURO-IV regulations. The application of a variety of technologies to make the engine both lighter and more compact, including a new casting process for the cylinder block, and the use of advanced combustion and friction reduction technologies have resulted in a balance of power output, fuel efficiency and quietness at the top of this engine class. The employment of these original technologies has fully realized the development concept, which stresses both power and refinement. The new Accord equipped with this newly developed diesel engine has been well received in the European market.

1. Introduction

Concern for environmental issues is growing world wide, including in Europe where there is a strong sense of urgency concerning global warming. Europe has been striving to continue to reduce CO₂ emissions and has recently developed a large market focused on diesel engines, as they provide high performance. Honda has been engaged in the development of fuel economic and environmental futuristic technologies such as: Compound Vortex Controlled Combustion (CVCC)⁽¹⁾, Variable Timing and Lift Control Technology (VTEC)⁽²⁾, Compressed Natural Gas Engine (CNG)⁽³⁾, Electric Vehicle (EV)⁽⁴⁾, Hybrid⁽⁵⁾ and Fuel Cell vehicles⁽⁶⁾. The most recent development is a Turbocharged Diesel Engine, the Intelligent Common Rail Turbocharged Direct Injection (i-CTDi), which is the first for Honda.

Figure 1 shows an external view of the engine while Table 1 shows its main specifications.



Fig. 1 External view of i-CTDi diesel engine

* Tochigi R&D Center

Table 1 Main specification of i-CTDi diesel engine

Engine type	DOHC-4VLV
Displacement (cm ³)	2 204
Bore × Stroke (mm)	85 × 97.1
Compression ratio	16.7
Fuel injection system	Common rail
Maximum power (kW/rpm)	103/4 000
Maximum torque (Nm/rpm)	340/2 000

2. Development Concept

The design goals for this project were to develop the diesel engine's strength of good fuel efficiency to the extent possible while holding its weaknesses of noise and vibration to a minimum.

The newest diesel engines are not inferior to gasoline engines on a comparison of power output; in fact there are many cases where diesel engines surpass gasoline engines. This can be considered to be one of the strengths of diesel engines; however, the diesel's very good fuel efficiency, not achievable by current gasoline engines, is considered as its most significant strength.

In comparison with a gasoline engine, a diesel engine loses some appeal due to its vibration and noise. In recent years, along with power output, progress has been made in these areas; however, its unique combustion noise cannot be overlooked. It is expected that an engine that overcomes these demerits, and achieves the same levels of noise and vibration (NV) as a gasoline engine, would be widely accepted.

Another natural basic consideration of an engine development project is the environment. If the engine can be developed to meet EURO-IV emissions regulations, which will be required in 2005, while keeping superior fuel economy and achieving gasoline engine alike NV, the engine is considered well balanced.

An engine with these merits is defined as a "First Class Diesel Engine" in a general term. Once the targets were clarified, the direction of development was easily established. The following three core technologies were pursued to achieve this concept.

- (1) Lightweight, highly rigid structure
- (2) Highly precise combustion control
- (3) Extremely efficient exhaust cleanup system

3. Lightweight, Highly Rigid Structure

A lightweight rigid structure is very important for achieving high fuel efficiency and low NV. During the development of the new diesel engine, Honda expanded its strength capability with casting aluminum⁽⁷⁾⁻⁽⁹⁾ and developed a closed deck aluminum cylinder block with a high productivity.

One of the most prevalent methods for manufacturing aluminum blocks is the use of high pressure casting. This has a high productivity; however, difficulties arise such that sand cores cannot be used due to the high pressure and gas intrusion leading to heat processing difficulties. On the other

hand, the cylinder pressure in a diesel engine is high; therefore a closed deck type is advantageous. Thus, to meet both of these criteria, a manufacturing method injecting semi-solid aluminum into a metal mold at low pressure referred as "Advanced Semi-solid Casting Technology" (ASCT) was developed. This provides both high productivity and a closed deck engine structure. Figure 2 shows an overall diagram of the cylinder block. In addition, an annealing process and thinner walls make it possible to achieve a 30% reduction in weight when compared to cast iron block diesel engines in the same class. This is described in Fig. 3.

The sleeves are made of cast iron using a spin casting process. The thickness other than the outer spines (protrusions used for adherence) was reduced to 3 mm. Also, the thickness of the aluminum between the sleeves is 3 mm, giving a total of 9 mm between cylinders, which is the same as for a gasoline engine.

Another characteristic of the cylinder block is the cylinder offset. The crank center was offset 6.5 mm to the thrust side of the bore center. This has reduced the impact energy of the piston by 30%. Figure 4 shows the simulation results. This has produced both a reduction in NV and an improvement in fuel efficiency.



Fig. 2 Photograph of ASCT aluminum cylinder block

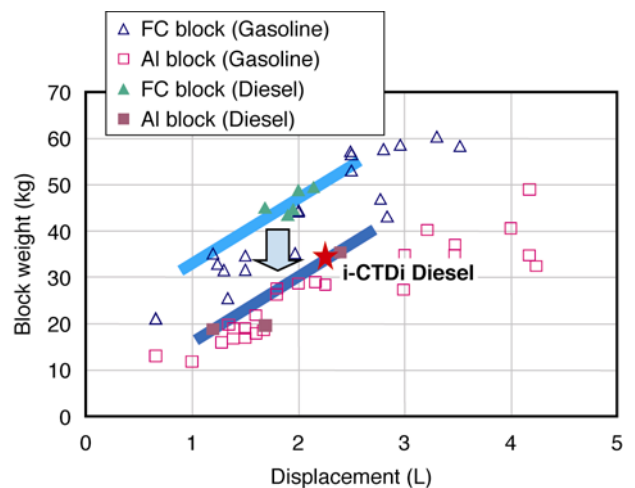


Fig. 3 Effect of ASCT on weight of cylinder block weight

The main bearing is supported by the lower block structure that is made of die cast aluminum, which contributes to the engines high rigidity.

In order to reduce friction at low coolant temperatures, cast iron bearing holders are being cast in a mold. Through this type of construction, as can be seen in Fig. 5, this aluminum block has achieved the same high rigidity as one made of cast iron.

In order to reduce the weight of the crankshaft, a four counterweight type was adopted and the crankshaft was strengthened using high frequency quenching⁽¹⁰⁾. The diameter of the main/pin journal is 60/50 mm. The bearing includes a recently developed high surface pressure solid lubricant overlay to respond to the low viscosity of the recent engine oil. This improved the boundary lubricant characteristics and made possible the use of low viscosity 0W-20 class engine oil. Furthermore, targeting improvement during the breaking in period, a molybdenum disulfide coating was added to the surface.

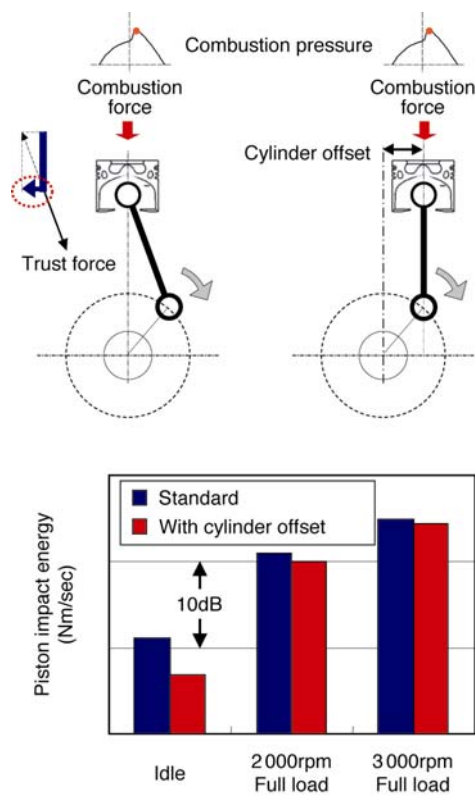


Fig. 4 Effect of offset cylinder on thrust force

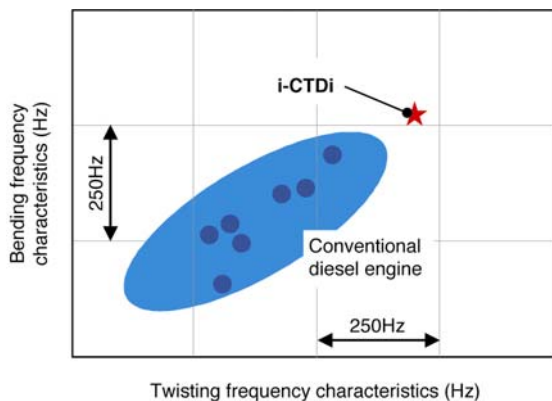


Fig. 5 Dynamic characteristics of cylinder block

The cylinder head contains vertical valves, direct injectors, glow plugs, etc. in a small area leading to a complex structure that has a high thermal load. Therefore, a top-feed cooling method is applied, that is, coolant that has been cooled by the radiator first cools the cylinder head, then the cylinder block and then each of the auxiliary systems. A cylinder head diagram is shown in Fig. 6 while Fig. 7 shows the schematic diagram of the cooling system. Through use of this cooling method, as can be seen in Fig. 8, heat removal of all parts of the head was improved compared to the conventional cooling method, where the cylinder block is cooled first.

In order to use center injection, DOHC 4 valves were used for the valve train. Coupling with the roller rocker arm contributes to the lowering of friction. Also, to help make it maintenance free, hydraulic lash adjusters (HLA) are used.

A single roller chain is used to move the valves. A diesel engine has large fluctuations of engine rotation that place a large load on the drive chain, therefore a silent chain would

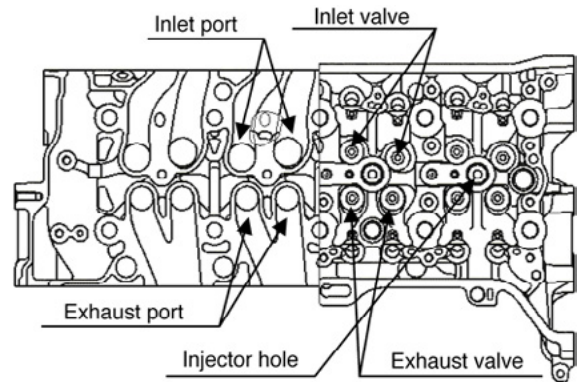


Fig. 6 Detail of cylinder head

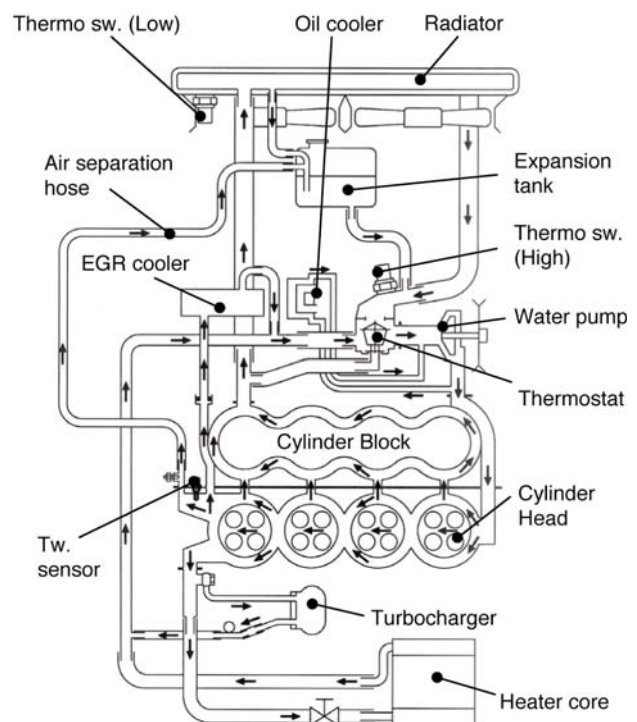


Fig. 7 Schematic diagram of cooling system

be required to be extremely wide. Also, soot in the engine oil causes pitting wear on a bush chain. Therefore, a roller chain that is processed with Vanadium Carbide (VC), which has excellent wear resistance, is used. Drive transfer between the intake and exhaust camshafts is performed by a helical gear with a scissors gear attached. This provides both a reduction in NV and compactness.

In order to reduce NV, a secondary balancing system is used. Targeting the compactness, the balancing unit is driven by a single chain, like the camshaft and is placed in the oil pan. Figure 9 shows an overall diagram of the drive train system. In order to reduce both aeration of the oil and friction, optimization of the balancing unit case structure was performed. Also, the oil pump is driven from the same shaft as the balancer unit providing a synergistic use of components.

The auxiliary systems are grouped at the front of the engine and driven with a serpentine belt. This helps make the

system compact. Also, the aluminum housing of the recyclable oil filter is put to further use as an auxiliary bracket providing synergy and making the system more lightweight. The auxiliary systems are shown in Fig. 10.

In order to reduce NV of the i-CTDi a dual mass flywheel is used along with a torque fluctuation absorbing crank pulley used to reduce tension in the auxiliary system belt. However, because the system passes through a resonance area during start up, a pulley with a one-way clutch was applied to the alternator, which has the most inertial mass of the auxiliary systems.

4. Highly Precise Control of Combustion

The combustion chamber is a re-entrant style 4 valve central injection chamber. To develop a combustion that produces high fuel efficiency, low noise and clean exhaust it needs to be homogeneous and smooth. As shown in Fig. 11, the chamber shape was optimized after reviewing several types of combustion chambers. Also, the compression ratio is set to 16.7, which reduces friction. Afterglow control, energizing the glow plugs after startup, was implemented for combustion improvement at a low coolant temperature and it ensured a stable combustion during this period. Arranging the valves vertically and eliminating the valve pockets in the upper surface of the piston led to a low Surface to Volume (S/V) ratio of 0.643 (1/mm), compatible with the clean concept. Details of the shape of the combustion chamber can be seen in Fig. 12.

To achieve the best possible combustion, having many degrees of freedom of control as well as highly precise control is essential. Several of the devices used on the i-CTDi are changed to electronic control. The control system diagram is shown in Fig. 13.

The fuel injection system used for the engine is the BOSCH common rail system. The high pressure injection pump is driven by a sub-shaft placed at the end of the exhaust camshaft and achieves a maximum pressure of 1 600 bar. To obtain optimal efficiency in the reduction of gear ratio, it is set at a rotational speed of 5/6 of the engine speed. Targeting

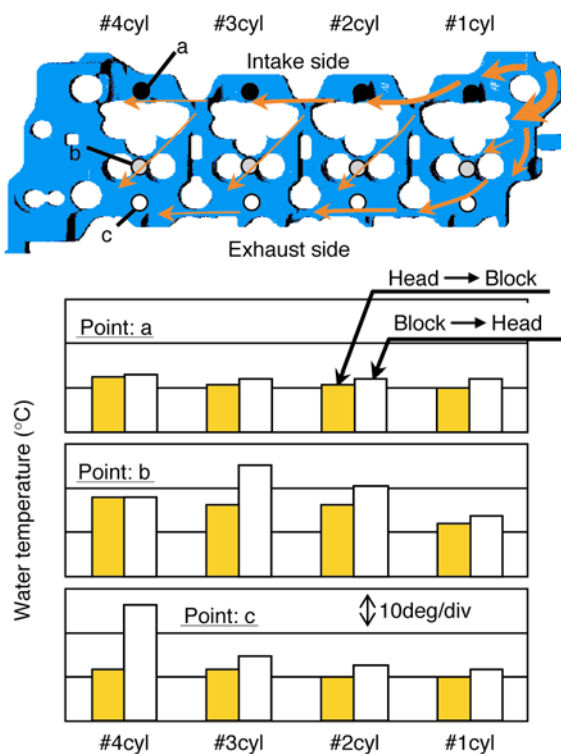


Fig. 8 Effect of top feed cooling system

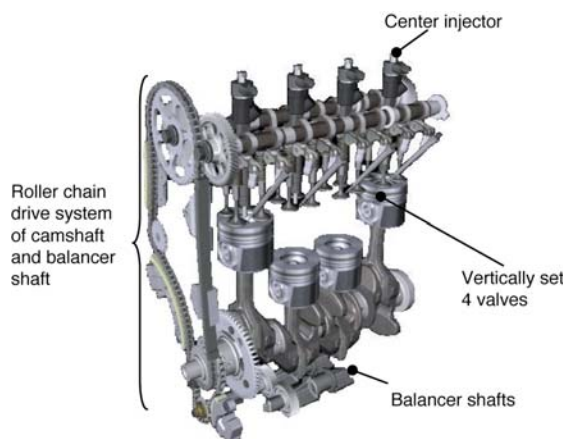


Fig. 9 Schematic diagram of drive train system

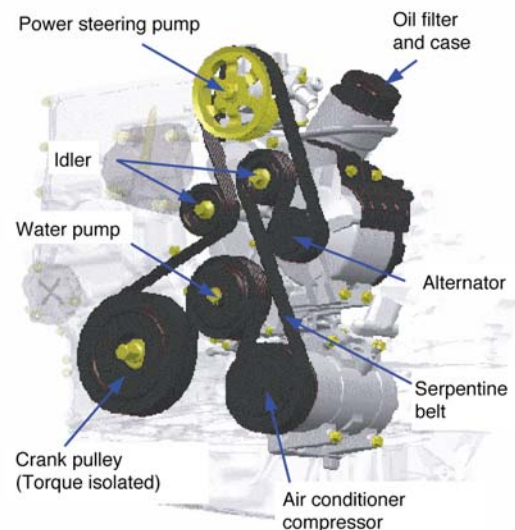


Fig. 10 Schematic diagram of auxiliary device drive system

low NV between the camshaft and sub-shaft a helical gear with a scissors gear attached is used for transfer of power. Also, an Oldham coupling is used to transfer power from the

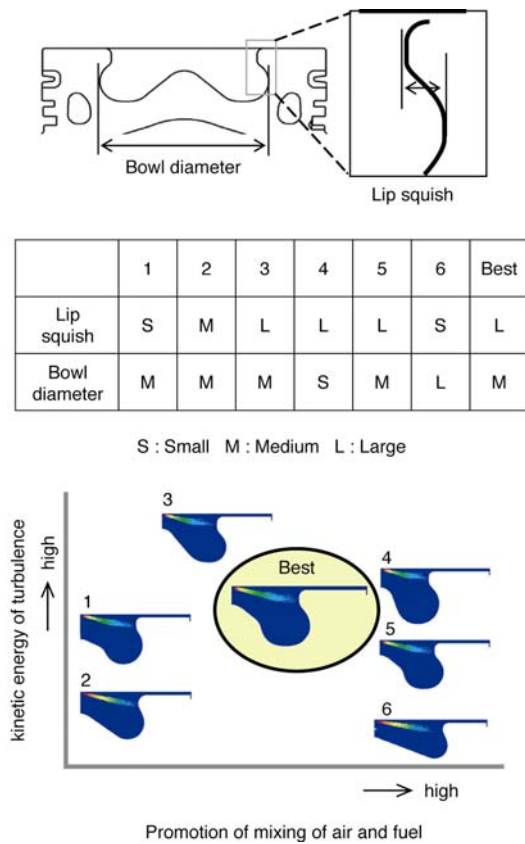


Fig. 11 Test result of various type of combustion chamber

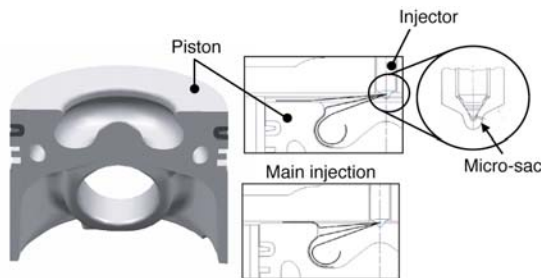


Fig. 12 Detail of the combustion chamber

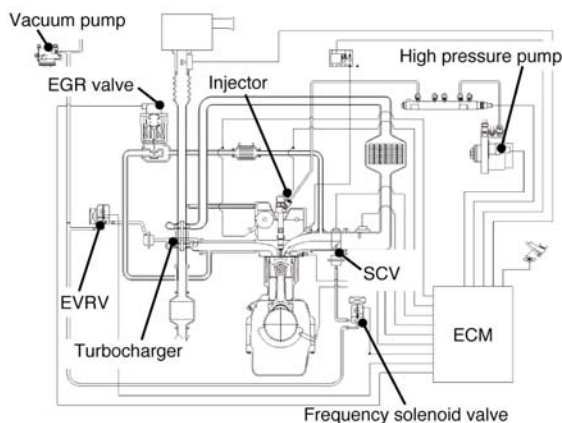


Fig. 13 Schematic diagram of total control system

sub-shaft to the high pressure pump. A system overview diagram is shown in Fig. 14. Also, a 6 hole micro-sac spray nozzle that has small spray pattern variability and suppresses Particulate Matter (PM) emissions was adopted.

The i-CTDi is equipped with a variable linear swirl control valve (SCV). This provides optimum and precise swirl control over the entire range of engine speeds leading to optimum combustion. As can be seen in Fig. 15, the SCV valve is placed upstream of the tandem intake manifold, containing two independent ports and chambers, and is situated to avoid direct contact with exhaust gas recirculation (EGR) gases. This has provided a simple yet highly reliable SCV system. The two ports are the primary port, which is a swirl port and the secondary port which is a straight port arranged directly in line with the combustion chamber. As can be seen in Fig. 16, swirl ratios from 1.2 to 4.0 are achieved with low intake resistance. A sensor is used to

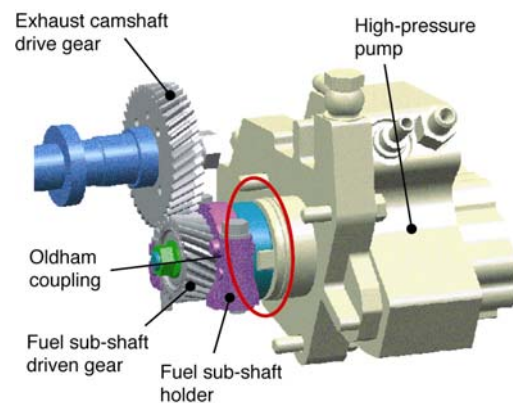


Fig. 14 Schematic diagram of drive system of high-pressure pump

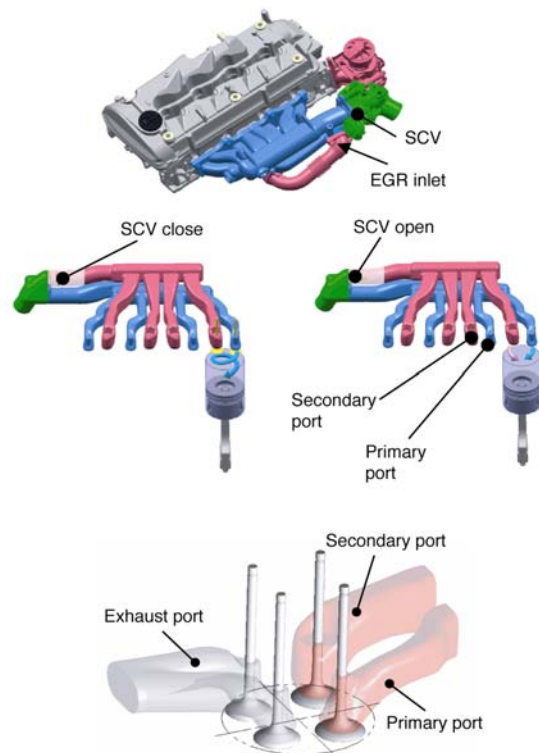


Fig. 15 Schematic diagram of intake system

determine how much the SCV valve is open and a frequency solenoid valve with electronic control is used to operate the valve with vacuum. Figure 17 shows the settings of the SCV valve opening.

EGR, used for NO_x reduction has a large effect on combustion quality. Therefore, the EGR valve is controlled with an electronically controlled linear solenoid that provides unparalleled control capability, high precision, and improved response. As the linear solenoid type requires less force to operate compared to the vacuum driven type, the double poppet type is used in a structure that cancels the characteristic exhaust back pressure of a turbocharged engine. This is described in Fig. 18.

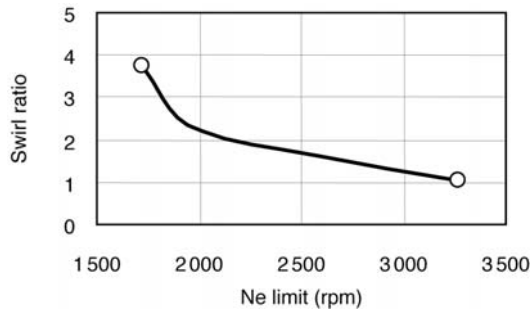


Fig. 16 Relationship between Ne limit and swirl ratio

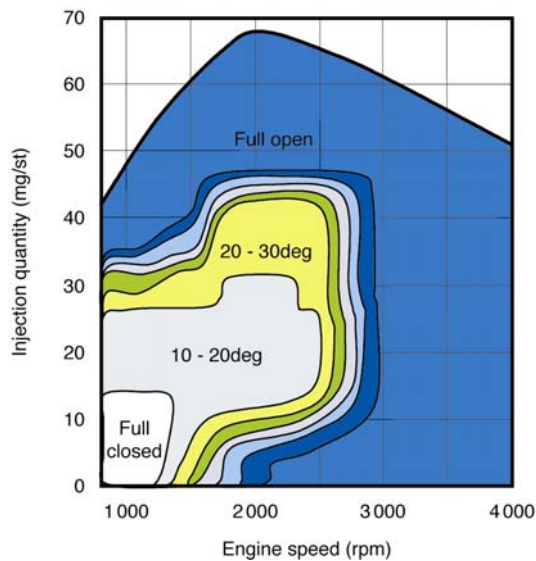


Fig. 17 Control map of SCV

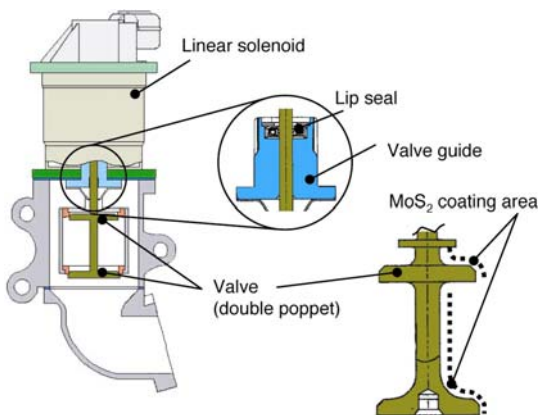


Fig. 18 Cross-section of electrically controlled EGR valve

A shield was placed to suppress exhaust from penetrating the valve guide and a MoS₂ coating is used to prevent sticking on the valve seat of residue from unburned fuel. High reliability was achieved. Also, the water cooled EGR cooler is placed downstream from the EGR valve and through increasing the density of the EGR, it improved the efficiency of reducing NO_x.

For the turbocharging system a variable geometry turbo charger is employed. Through optimizing the settings of both the compressor and the turbine, optimized turbo charging is available at all speeds. The geometry is controlled with an Electric Vacuum Regulating Valve (EVRV), a vacuum electronic control. The targeted turbo charger pressure is detected inside the intake manifold and the vanes are opened or closed accordingly for geometry control. The center housing is cooled by coolant, protecting the materials that can be damaged by heat such as the engine oil and the bearings. Also, an air to air intercooler is used, concluding with a maximum turbo-charger pressure of 130 kPa being obtained.

5. Highly Efficient Exhaust After-treatment System

On top of reducing the amount of engine feed gas, a highly efficient exhaust after-treatment system is essential to achieve EURO-IV exhaust regulations. A new diesel engine exhaust after-treatment system was developed for the i-CTDi engine. Figure 19 shows a system diagram of this exhaust after-treatment system.

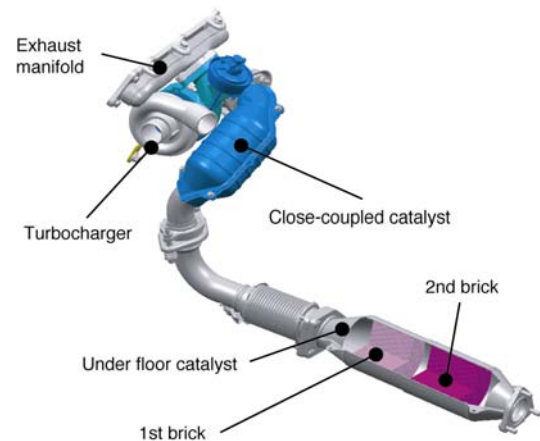


Fig. 19 Schematic diagram of exhaust system

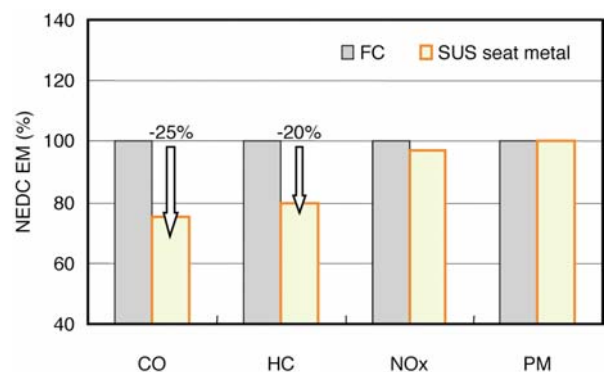


Fig. 20 Effect of seat metal exhaust manifold

Table 2 Main specification of catalyst

	Close-coupled catalyst	Under floor-catalyst	
		1st brick	2nd brick
Type	Oxidation	De-NOx	De-NOx
Volume (L)	0.7	1.0	1.3
Substrate	Metal foil	Metal foil	Metal foil
Foil thickness (mm)	0.03	0.03	0.03
Cell density (cps)	400	400	400
Coating	Pt base	Pt base	Pt base
Zeolite	A	A	B

Through using an extremely compact press type exhaust manifold made of stainless steel, its thermal mass was reduced, therefore the light off characteristics of the catalyst is improved. As can be seen in Fig. 20, compared to a cast iron manifold, CO and HC emissions were reduced 20 to 25 %.

The main specifications for the catalyst are shown in Table 2. The catalysts consist of a close coupled oxidation catalyst and an under floor catalyst with 2 De-NOx reduction catalytic beds with different temperature based selective NOx clean up capabilities, shown in Fig. 21. This expands the temperature window of and optimizes NOx clean up. Also, on a component basis, 0.03 mm thick metal foil has better heat transfer and heat diffusion characteristics than ceramic. Through using metal foil for the catalyst, low temperature oxidation light off performance improved, and oxidation and NOx clean up performance is maintained in a high level balanced design.

6. Main Performance Characteristics

Figure 22 shows the power output performance of the i-CTDi engine. The maximum output of the i-CTDi shows a performance at the top of its engine displacement class. The acceleration capability in low to mid speeds is an important output setting. Therefore it is considered that the engine will perform well from city to freeway driving in a wide range of driving conditions.

The European Accord that is equipped with this i-CTDi engine coupled with a 5MT achieved a fuel efficiency of 5.4 L/100 km in the EUDC mode, the top of its class. It also meets the EURO-IV emission requirements.

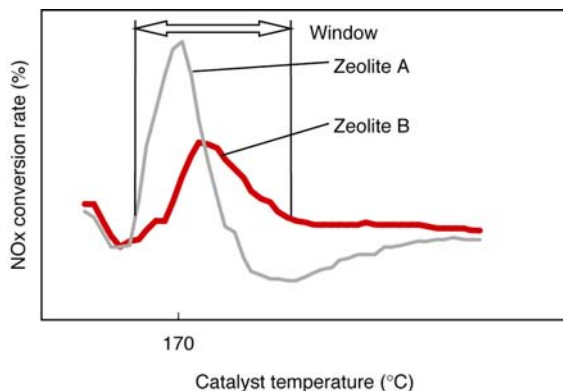


Fig. 21 Thermal characteristics of De-NOx catalyst

This Accord also has the best NV level of all of the diesel engines in the same class as shown in Fig. 23. Therefore, it is considered that the fundamental design concepts were achieved.

7. Conclusions

From a fundamental concept of “First Class Diesel Engine”, a turbocharged diesel engine, the i-CTDi, was developed with the goals of achieving high fuel efficiency and low NV.

- (1) The combustion is optimized by using a 1 600 bar common rail system. EURO-IV emissions regulations are met early through the combined use of De-NOx catalysts, a water cooled EGR cooler, and a continuously variable swirl control valve.
- (2) Through a new manufacturing process, starting with a lightweight aluminum cylinder block and roller chain, engine frame technology has led to a more compact engine with a large reduction in weight.

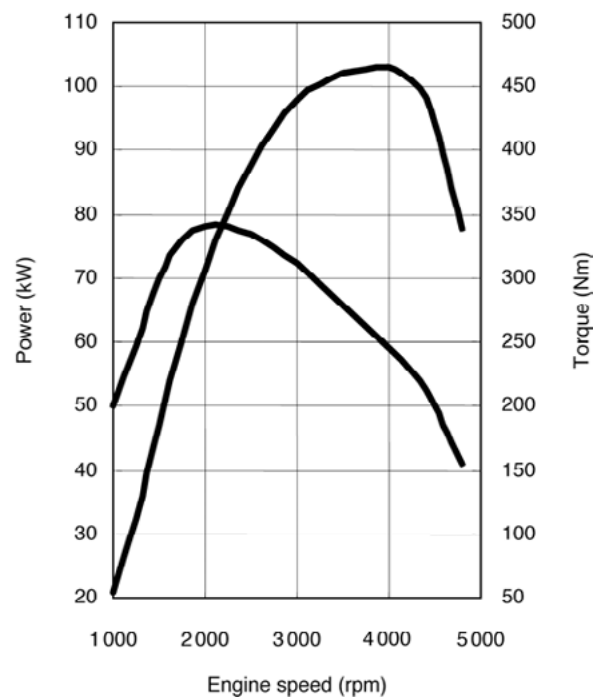


Fig. 22 Power curve of i-CTDi diesel engine

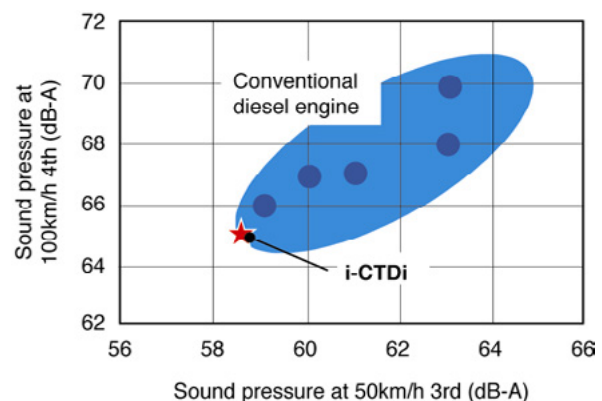


Fig. 23 NV level of i-CTDi diesel engine

- (3) Through low friction technologies, including combustion technology, a variable turbo charger, and an offset crankshaft, the engine has simultaneously achieved power output and fuel efficiency at the top of its class.
- (4) Through combustion control and increasing the engine frame rigidity, this engine achieved a level of silence similar to that of a gasoline engine.

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■ Authors ■



Tomoya ABE



Kenichi NAGAIHIRO



Yoshihito TSUJI



Kiyoshi TSUKIMURA



Hirokazu OHSAKI



Kazunori OZAWA