

Development of High-pressure Fuel System for 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 is employed in a newly developed direct injection gasoline engine. The high-pressure fuel injector is highly responsive, with a minimum injection timing of 0.7 msec, and injects an ultra-atomized spray with an average droplet diameter of less than 12 μm . To ensure durability and reliability in this original center injection system, the high-pressure fuel injector mounting employs a layout in which arm holders secure the unit. The design of the high-pressure fuel supply lines is optimized using simulations. In addition, high reliability is achieved by the reduction of stress and the adoption of a structure to dampen fuel pulsation. A simple plunger and spill solenoid system is employed in the high-pressure fuel pump enabling the reduction of the required driving force, the reduction of the component size, and the achievement of high-accuracy fuel pressure control.

1. Introduction

In response to the increasing demand for fuel economy in recent years, Honda developed a 2.0L direct injection gasoline engine. Mass production direct injection gasoline engines to date have most often been side injection systems with the injectors located on the side of the engine's combustion chamber.

This new engine gives the maximum in fuel economy improvements with ultra lean stratified charge combustion available in a direct injection gasoline engine, and at the same time adopts a center injection system to achieve excellent emission and power performance. As a result, best-in-class fuel economy is achieved by combining a highly accurate fuel injection control system and a high-performance lean NO_x catalyst. At the same time, the engine meets the strictest Japanese emissions standards.

This paper reports on the newly developed high-pressure fuel system and components for the center injector, direct injection engine.

2. System Outline

Figure 1 shows the fuel supply system adopted in the newly developed direct injection gasoline engine. The fuel is sent from the fuel tank by a low-pressure fuel pump at a pressure of 343 kPa. This is the same pressure as the port injection fuel supply system. The pressure of the fuel is raised by a high-pressure pump located on the engine, and the fuel is supplied to the high-pressure fuel injectors (referred to as injectors hereafter) through a delivery pipe. The fuel pressure is controlled so that it is normally 10 MPa, 8 MPa when idling, and 10.5 MPa at full load. The major features of

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the high-pressure fuel system for direct injection gasoline engines are as follows:

- (1) Adoption of highly responsive, ultra-atomization spray injectors that meet the requirements of a center injection system.
- (2) Adoption of mountings that secure the injectors using arm holders, giving both combustion gas seal reliability and injector durability and reliability.
- (3) Adoption of a fuel pulsation damper delivery pipe having a large capacity chamber and fuel feed pipe orifice structure; as well as a high-pressure fuel relief return system in case of an abnormal fuel pressure rise.
- (4) Adoption of a high-pressure fuel pump that uses a simple plunger and spill solenoid control system, providing a compact system and a cam drive requiring low drive force.

Details of each of these features are given below.

3. High-pressure Fuel Injector

3.1. Injector Structure

The injector structure is shown in Fig. 2. The basic structure follows that of an electromagnetic solenoid system injector used in port fuel injection gasoline engines. The

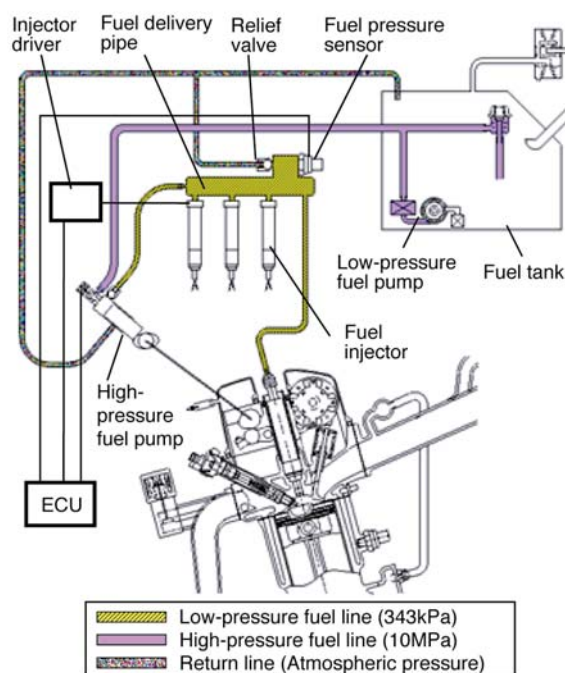


Fig. 1 High pressure fuel supply system

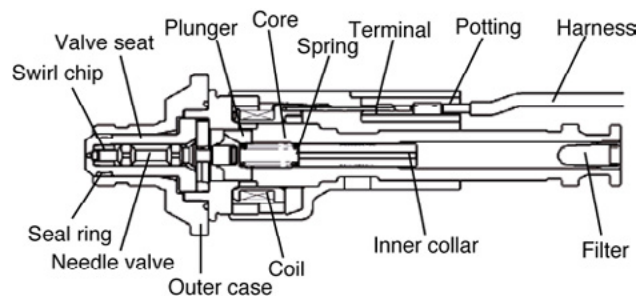


Fig. 2 Cutaway view of high-pressure fuel injector

features of an injector for direct injection gasoline engines are as follows:

- (1) Adoption of a high efficiency magnetic circuit that satisfies the requirements for high responsiveness and a wide range of flow characteristics.
- (2) Adoption of an inner collar that reduces the diameter of the fuel passage, thereby reducing pulsation occurring inside the injector.
- (3) Adoption of a swirl chip that creates an ultra atomized, narrow angle, high-penetration spray.
- (4) An outer case at the end of the injector is provided that forms a combustion gas sealing gasket surface between the engine head and the injector.
- (5) A seal ring is provided, which uses poly tetra fluoro ethylene resin (referred to as PTFE resin hereafter) to make a combustion gas seal between the outer case and the valve seat.
- (6) The elimination of a direct connector and using of a harness drawing structure that seals the wire connection part.

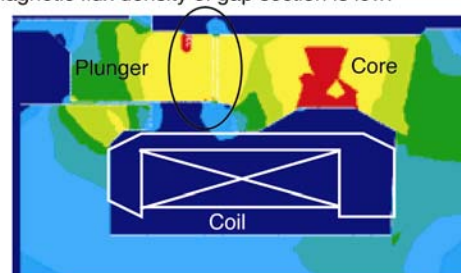
3.2. Highly Responsive with a Wide Range

In the ultra lean stratified charge combustion range of the injector for direct injection gasoline engines, it is necessary to discharge the fuel in a short period towards the rising piston cavity to form a stratified charge fuel mixture. In the fully loaded driving range, it is necessary to complete injection in the period from intake process through compression process. Therefore, high responsiveness and large flow characteristics are required.

In order to satisfy these requirements and maintain linear flow characteristics from the idling range to fully loaded driving range, the injector is designed with a high-efficiency magnetic circuit, providing the highest magnetic flux density in the aspiration gap section between plunger and core, without losses in the magnetic circuit. The design work was carried out with a magnetic simulation, as shown in Fig. 3. In addition, to reduce closed valve dispersion due to needle

[Inappropriate example]

Magnetic flux density of gap section is low.



[Appropriate example]

Magnetic flux density of gap section is high.

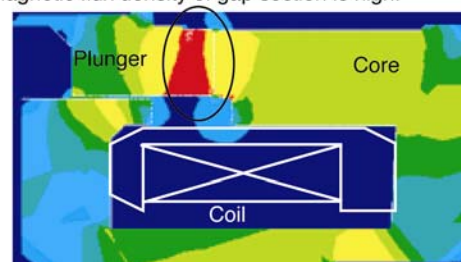


Fig. 3 Results of magnetism simulation

valve bouncing, the inner collar's fuel passage diameter was made smaller (diameter $\phi 1$ mm), and fuel pulsation occurring within the injector was damped, working toward stabilized flow in the low-pressure injection range.

The drive driver uses a 150 V voltage converter, and employs a drive current wave peak hold type driver, as shown in Fig. 4, thereby raising responsiveness. As shown in Fig. 5, peak current value is set at the point where open valve

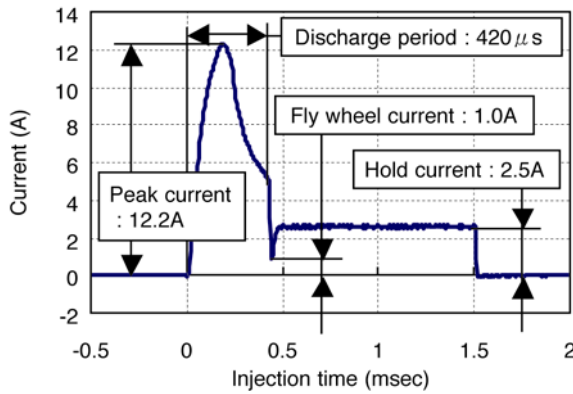


Fig. 4 Injector current wave

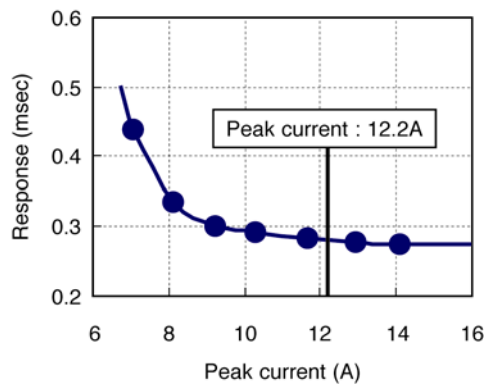


Fig. 5 Needle valve response and peak current

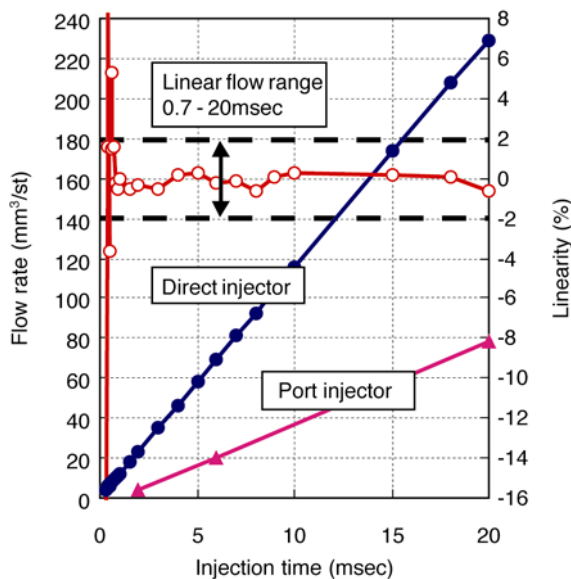


Fig. 6 Injector flow rate

responsiveness is at its best and current value is at its lowest.

As shown in Fig. 6, these improvements result in highly responsive and wide range flow characteristics. Linearity is maintained to the shortest injection time of 0.7 msec, and at the same time, an injection flow rate at least twice that of a port injection injector is obtained.

3.3. Spray Characteristics

With direct injection gasoline engines, the injectors inject fuel directly into the combustion chamber and the air-fuel mixture burns. This requires the injectors to have ultra atomized spray. In addition, in order to create the stratified charge fuel mixture according to the independent center injection combustion concept, as shown in Fig. 7, the injector must have a spray with a tight spray angle of 25 deg., and have a high spray penetration. Figure 8 shows the spray angle when the injector is spraying its full amount. Figure 9 shows the spray penetration at a fixed time after the injector has completed injection.

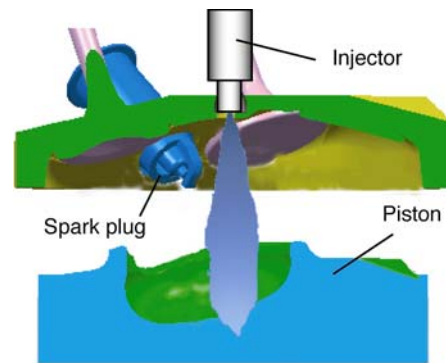


Fig. 7 Concept of combustion in direct injection gasoline engine

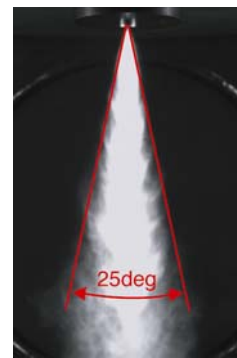


Fig. 8 Spray angle of newly developed injector

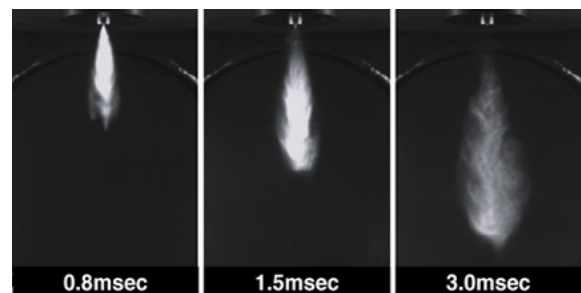


Fig. 9 Spray penetration of newly developed injector

In order to obtain ultra-atomization spray, a normal fuel pressure of 10 MPa was adopted, making it possible to create droplets having Sauter's Mean Diameter (referred to as SMD hereafter) of $12\text{ }\mu\text{m}$ or less, as shown in Fig. 10. It is known that the higher the fuel pressure is, the smaller the particle diameter becomes (ultra atomization)⁽¹⁾, and as shown in Fig. 11, this injector is designed so that particle diameter is at its best at 10 MPa.

In spray creation, by optimizing the proportion of straight flow and swirl flow using the swirl chip flutes positioned at the very end of the passage within the injector, as shown in Fig. 12, it is possible to obtain a superior balance between spray angle, spray penetration, and particle diameter.

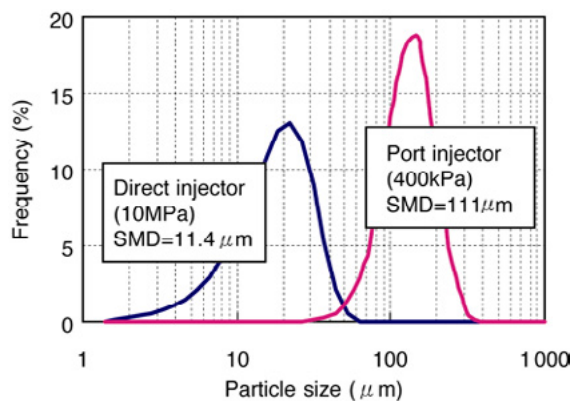


Fig. 10 Comparison of SMD between conventional port injector and high-pressure direct injector

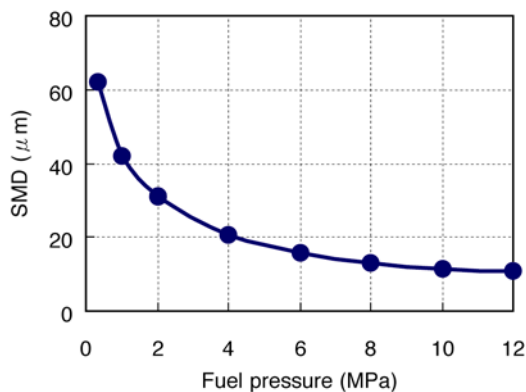


Fig. 11 Relationship of SMD and fuel pressure

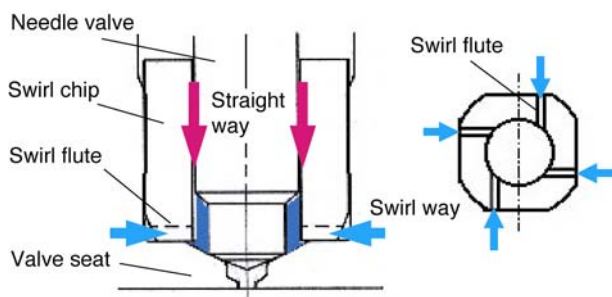


Fig. 12 Configuration of injector swirl guide

3.4. Center Injector Mounting Structure

In order to establish the independent center injection layout, it is necessary to resolve the following issues:

- (1) Combustion gas seal that is highly reliable.
- (2) Lowering of injector valve seat temperature as a countermeasure to deposits clogging the injector nozzle.

In order to achieve these, an arm holder structure is adopted, as shown in Fig. 13. This structure can often be seen as a mount for fuel injection nozzles used on diesel engines, and is adopted for this direct injection gasoline engine as well.

A metal gasket is adopted for the combustion gas seal around the outside of the injector, as shown in Fig. 14, and by setting the injector seat on the cylinder head side, a gasket seal surface is formed. On the injector tip gasket on the combustion chamber side, a gasket without a rubber coating is established as a firewall, and the valve seat tip temperature is lowered. A gasket with rubber coating is used at the upper levels of the injector, creating a complete seal structure. In order to seal these gaskets, a holder is placed around the outside of the injector, and an outer case at the end of the injector. Then, axial force is applied through the medium of an arm from the top of the cylinder head.

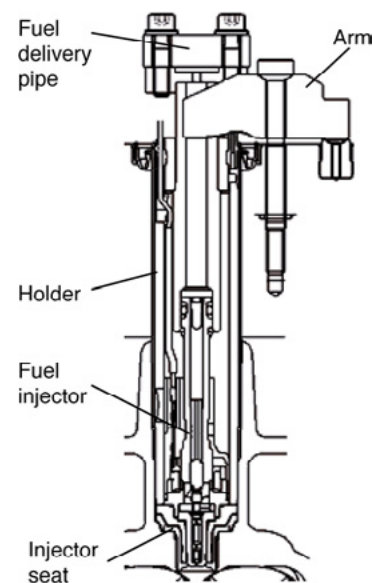


Fig. 13 Installation of injector

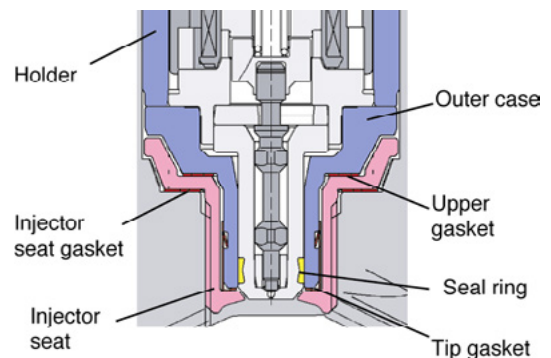


Fig. 14 Cutaway view of seal mechanism

In addition, a PTFE resin seal ring is used between the outer case and the valve seat to help prevent valve seat temperature rise due to combustion gas penetration. The PTFE resin in this seal ring behaves such that at low temperatures the volume reduces and there is a drop in seal performance. However, as shown in Fig. 15, by setting the volume of the seal ring at a charging rate of 100% or more of the volume of the seal groove in the valve seat, it is possible to have a combustion gas seal in an extremely low temperature environment.

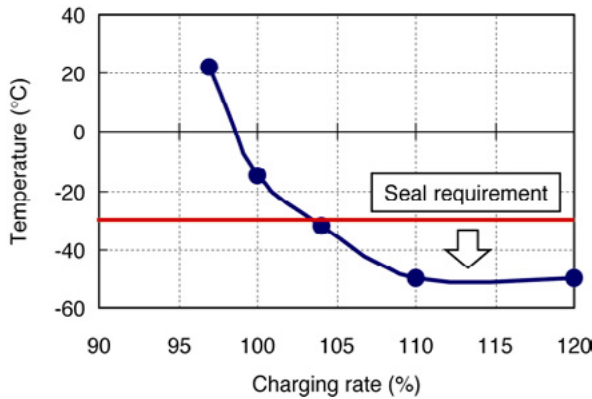


Fig. 15 Low temperature seal ability of seal ring

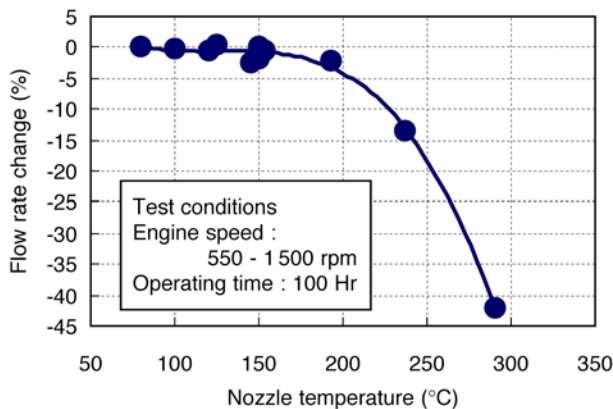


Fig. 16 Influence of nozzle temperature on flow rate

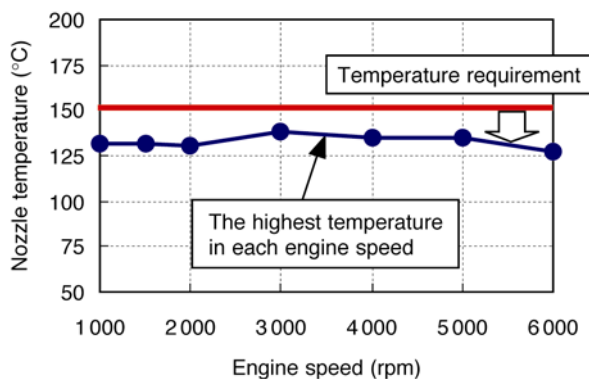


Fig. 17 Relationship of nozzle temperature and engine speed

It is known that if the valve seat temperature of injectors for direct injection engines exceeds 160 °C, there is a tendency for an increase in flow deterioration due to adhesion of deposits in the nozzle^{(2), (3)}. The test results for the new engine are shown in Fig. 16. By using the aforementioned combustion gas seal structure, the injector valve seat temperature, as shown in Fig. 17, remains below the development target of 150 °C at all engine speeds, preventing any reduction in injector flow after actual vehicle endurance driving.

In addition, by giving the injector end a shape that follows that of the combustion chamber, creating a structure whereby the combustion gas flow continually interferes with the nozzle, any accumulation of deposits on the injector edge is prevented.

4. High-pressure Fuel Supply Line

4.1. Fuel Delivery Pipe Reliability

The high-pressure fuel supply line structure, centered on the fuel delivery pipe, is shown in Fig. 18. For the fuel delivery pipe material, stainless steel for its corrosion resistance and superior resistance to stress caused by engine vibration. The feed pipe, which connects the high-pressure pump to the chamber, and the chamber to the injector, is designed using simulations. As shown in Fig. 19, simulations are made of static stress, considering location dispersion of fastening flange on the delivery pipe side and mounting flange on the mating side, and of dynamic stress considering engine vibration. It is confirmed there are no points of stress concentration. As a result, it is possible to create a reliable high-pressure fuel supply system, ensure reliability through simulation design, and confirm reliability through vehicle durability tests.

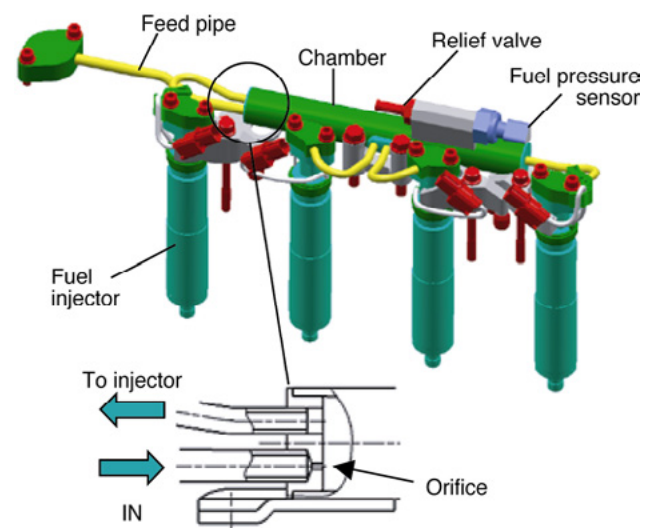


Fig. 18 Fuel delivery pipe

4.2. High-pressure Fuel Pulsation Countermeasures

The delivery pipe chamber has a capacity of approximately 80 cm³, with damping of pulsation occurring due to the high-pressure fuel pump discharge or injector operation working towards pressure stabilization. In the feed pipe that connects the high-pressure fuel pump and the chamber, an orifice is made at the chamber inlet. This orifice has the effect of damping resonance in the feed pipe that occurs due to high-pressure fuel pump discharge pulsation. This raises the durability and reliability of the O-ring seals in the fuel pipes. Figure 20 compares high-pressure fuel pump discharge pulsation waveforms with and without the orifice. It is clear that there is a dramatic reduction in pulsation due to the orifice.

4.3. High-pressure Fuel Relief System

Figure 21 shows the high-pressure fuel relief system. The pressure relief valve has a simple structure – a ball valve is seated in the valve seat with a spring. The relief valve's valve opening pressure is set at 12 MPa, for pressure relief in case of an abnormal fuel pressure rise. The structure is such

that fuel discharged from the relief valve is released into the fuel tank through a return pipe placed under the floor of the vehicle. The fuel delivery pipe relief valve discharges into the high-pressure fuel pump return line inside the engine bay.

5. High-pressure Fuel Pressure Control System

Figure 22 shows the high-pressure fuel pump structure. The exhaust camshaft is extended to have a double peak cam on it for the pump drive. The cam let the single plunger piston rise and fall, taking in and discharging fuel. As for fuel metering, the intake check valve opening and closing timing is controlled using a spill solenoid. Any excess fuel is emitted on the low-pressure fuel line side, with the required fuel discharged on the high-pressure line side. By using this spill solenoid fuel metering method, it is possible to drive the pump with the minimum required amount of work, and at the same time the unit can be very compact.

A large capacity pulsation damper is placed at the fuel inlet of this high-pressure fuel pump, absorbing pulsation that occurs when the excess fuel is emitted, raising the durability and reliability of the low-pressure fuel line.

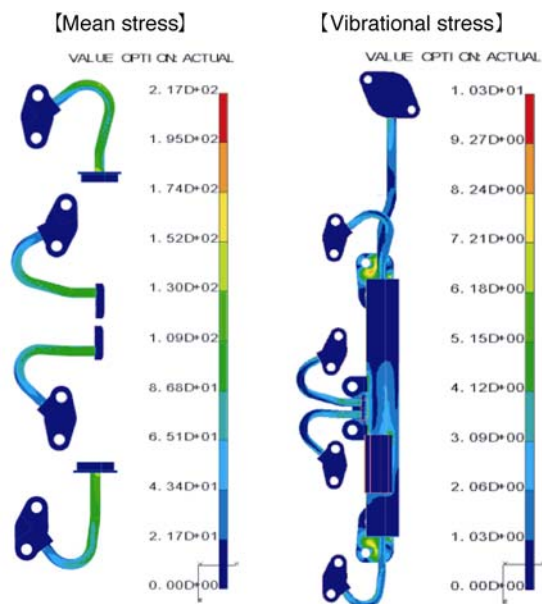


Fig. 19 Simulation results for mean stress and vibrational stress

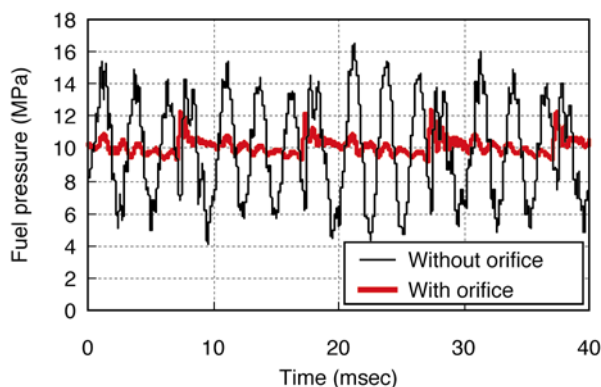


Fig. 20 Pulsation of high-pressure fuel pump

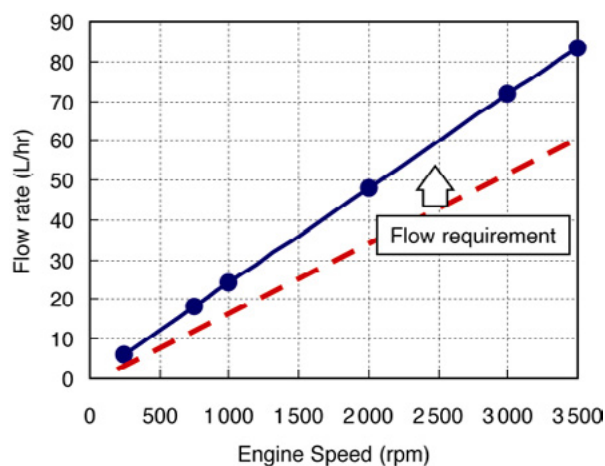


Fig. 21 High-pressure fuel relief system

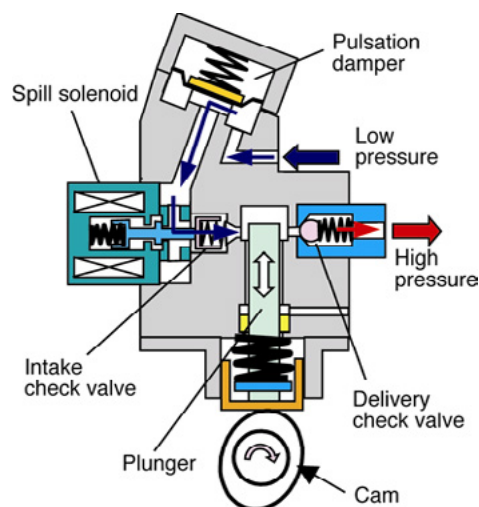


Fig. 22 Cutaway view of high-pressure fuel pump

The flow characteristics of the high-pressure fuel pump are shown in Fig. 23. It is clear that in comparison with the flow required when the vehicle is fully loaded, it is possible to obtain flow beyond the required amount.

The fuel pressure control method is shown in Fig. 24. As for the amount of discharge from the high-pressure fuel pump, the basic control variable is determined by the spill solenoid operation map, which is obtained according to the engine speed and injector discharge amount. Furthermore, by implementing feedback control that corrects the deviation between the pressure measured by a fuel pressure sensor placed in the fuel delivery pipe and the target fuel pressure using PID control, it is possible to control pressure at the target fuel pressure value. Adopting this fuel pressure control method enables highly accurate fuel pressure control.

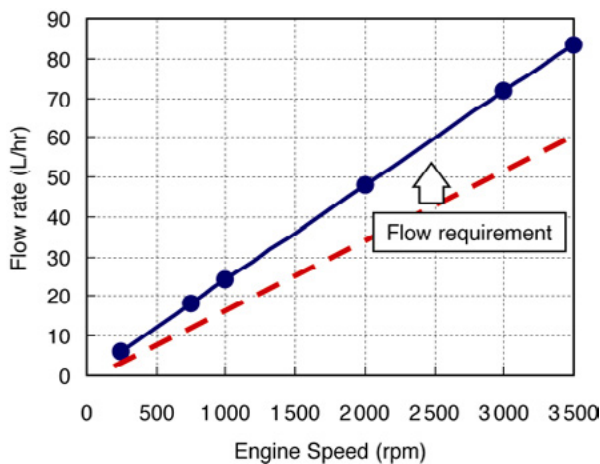


Fig. 23 Flow rate of high-pressure fuel pump

6. Conclusion

The following results are achieved in the development of a high-pressure fuel supply system for direct injection gasoline engines:

- (1) It is possible to obtain, with this high-pressure injector, linear flow characteristics from no load idling through fully loaded driving, through a high-efficiency magnetic circuit design, a smaller inner collar diameter, and a specially designed driver. In addition, by optimizing high fuel pressure and swirl guide settings, it is possible to obtain spray characteristics including particle diameter, spray angle and spray penetration, that match the center injection combustion concept.
- (2) By adopting an arm holder structure as the center injection system's injector mounting structure, combustion gas seal performance and injector tip temperature targets are met, making it possible to ensure durability and reliability.
- (3) Using various stress simulations for the feed pipe, and by placing a large capacity chamber and an orifice in the fuel feed pipe, it was possible to create a very reliable high-pressure fuel supply. In addition, providing a relief return system helps provide additional safety in the event of an abnormal fuel pressure rise.
- (4) By adopting a simple, cam driven plunger and spill solenoid control system, a compact and low drive force high-pressure fuel pump was achieved. The high-pressure fuel pressure control system enables highly accurate control by carrying out feedback control using a fuel pressure sensor, in addition to a basic control variable using a map.

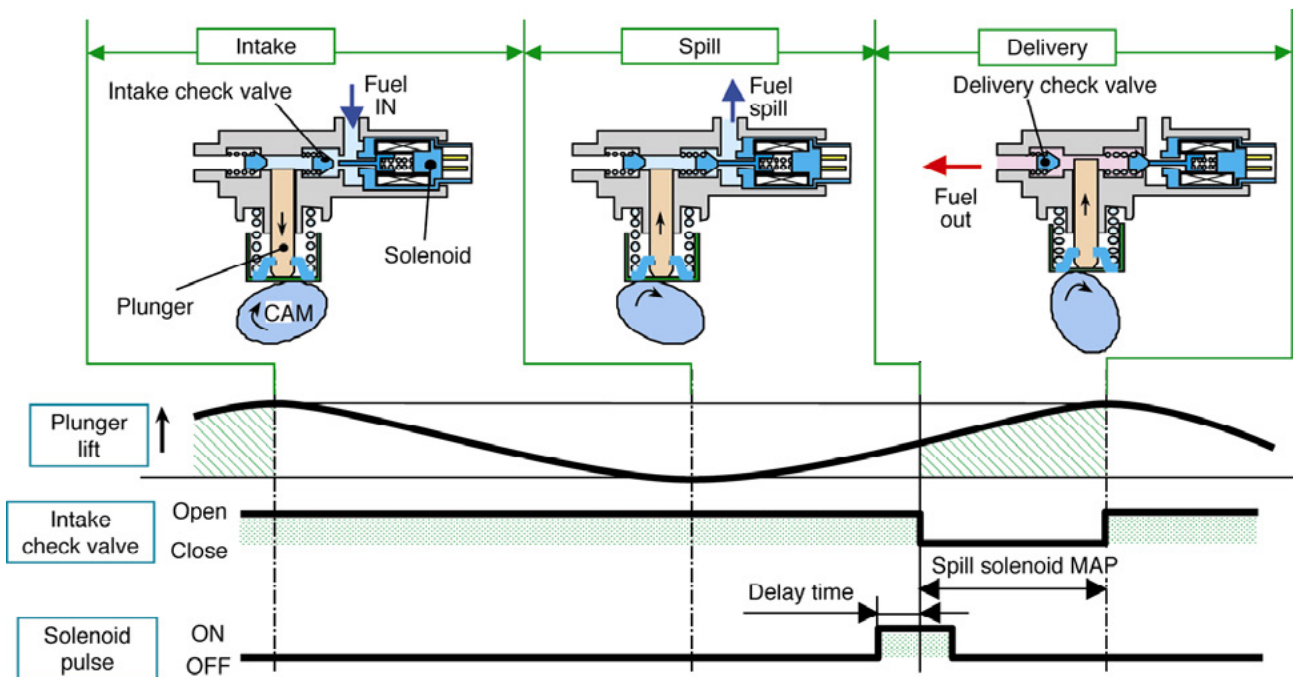


Fig. 24 Diagram of spill solenoid control

Acknowledgments

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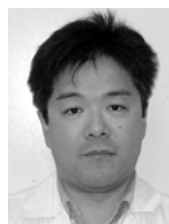
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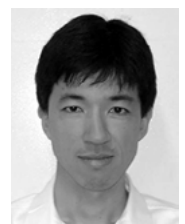
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