

Development of High-Pressure Fuel Supply System for Formula One Engine

Tetsuya TANAHASHI*
Yosuke SAWADA*

Kazuji ONO*
Atsushi SHIMIZU*

Masanori HAYAFUNE*

ABSTRACT

Important factors in boosting the performance of today's Formula One engines include: the realization of the formation of ideal air-fuel mixtures and the achievement of greater combustion efficiency, through the use of shorter fuel injection periods and increased spray atomization resulting from higher fuel pressures; and, in addition to this, the achievement of stable combustion in the low-load operating range.

A comprehensive analysis of injector spray characteristics was conducted, leading to the development of a Honda-made high-efficiency, high-pressure fuel supply system. This enabled the achievement of a 15 kW increase in engine power.

1. Introduction

The importance of development programs for fuel systems in automotive engines is increasing as a means of resolving technological issues related to increasing fuel efficiency and reducing exhaust emissions. Given this, automakers, parts makers, and research organizations are pushing ahead with the development of more advanced technologies, and are conducting more sophisticated analyses of relevant phenomena.

In Formula One engines, the fuel spray has a particularly significant effect on engine power, and optimum spray morphologies exist for specific combustion chamber shapes and intake port shapes. When specifications are changed in these areas, the fuel spray is also studied and redesigned.

Against this background, a basic principle of Honda's Formula One engine development program was the in-house production of fuel supply systems, in order to boost competitiveness through the ability to trace the development process and produce unique technologies.

This paper will provide a technological overview of a fuel pump for the supply of high-pressure fuel, a regulator to control fuel pressure, and an injector to inject the fuel and form a spray.

2. Mechanism of Power Increase with High-pressure Fuel Injection

During the development of fuel systems for Formula One engines, a single cylinder engine was used to conduct analyses of intake air and fuel phenomena.

Based on the results of these analyses, the high-pressure fuel systems were in use in race engines until 2006, and further modifications of the spray morphology from 2006 onwards helped to enable an increase in power of approximately 15 kW.

Figure 1 shows changes in the fuel pressure and power of Honda race engines, and Fig. 2 shows an

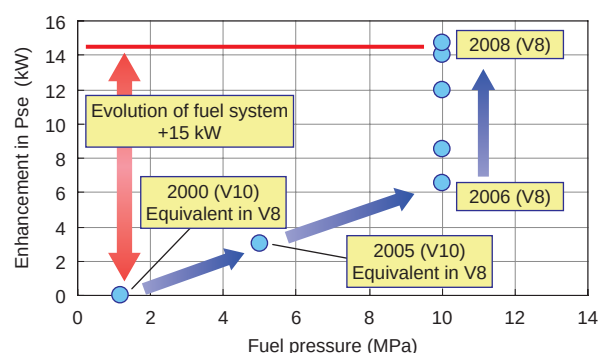


Fig. 1 Evolution of fuel system

* Automobile R&D Center

overview of the components of a fuel supply system.

The following three mechanisms can broadly be indicated as those responsible for the increase in power achieved when the fuel pressure was increased from its initial value of 1.2 MPa to 10 MPa and the spray morphology was modified:

- (1) Increased intake air cooling efficiency due to increased supply flow rate (shorter injection period)
- (2) Enhanced combustion due to greater atomization of the spray
- (3) Increased intake air cooling efficiency due to modification of spray morphology

2.1. Increased Intake Air Cooling Efficiency with Increased Supply Flow Rate

Under the initial specifications of a fuel pressure of 1.2 MPa and a supply flow rate of 43 L/h, the maximum injector supply flow rate was low because the fuel pressure was low, and a long injection period was necessary in each cycle. By contrast, the use of high-pressure fuel increased the supply flow rate and consequently reduced the injection period, helping to enable injection for an optimal injection period.

Figure 3 shows the relationship between the intake air velocity at the funnel tip and the injection period, as determined using simulations.

The results of this analysis show that the intake air cooling effect is maximized by ending the injection period by the timing of maximum blow at the funnel tip.

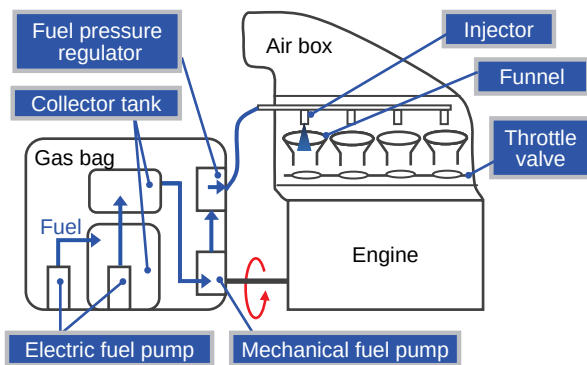


Fig. 2 Components of fuel supply system

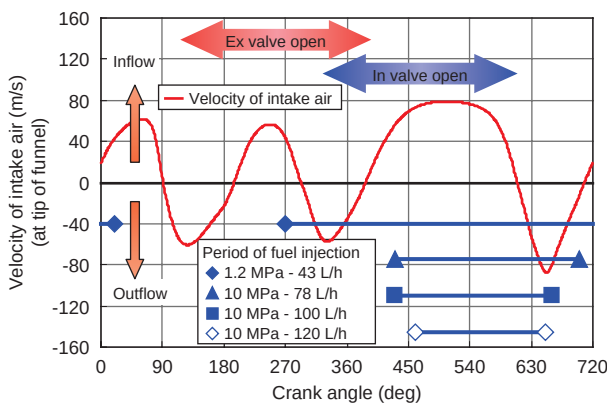


Fig. 3 Relationship between intake air velocity and injection timing

A decline in the temperature of the intake air can be determined from changes in the intake air pulsation. As Fig. 4 shows, a short injection period results in a phase delay in the intake air pulsation, and this can be judged as indicating that filling efficiency has increased due to a decline in intake air temperature.

2.2. Enhanced Combustion Efficiency with Greater Fuel Atomization

The diameter of the fuel droplets, which had been approximately 50 μm at a fuel pressure of 1.2 MPa, was reduced to 20 μm or less at a pressure of 10 MPa. As Fig. 5 shows, power was increased as a result of this refinement of the droplets. The mechanism behind this increase in power is thought to be increased mixing of the intake air and the fuel, and a reduction in the adherence of fuel to the port walls.

2.3. Increased Intake Air Cooling Efficiency with Modified Spray Morphology

As indicated above, the use of increased fuel pressure resulted in increased cooling air efficiency and increased combustion efficiency.

The fuel spray morphology was also studied in order to further boost these effects. Figure 6 shows changes in shaft output in a single cylinder test engine.

The increase in engine power that occurs when an increased number of injection holes are employed is due to increased atomization of the spray. The delay in the phase of intake air pulsation shown in Fig. 7 indicates that a decline in the temperature of the intake air has increased filling efficiency.

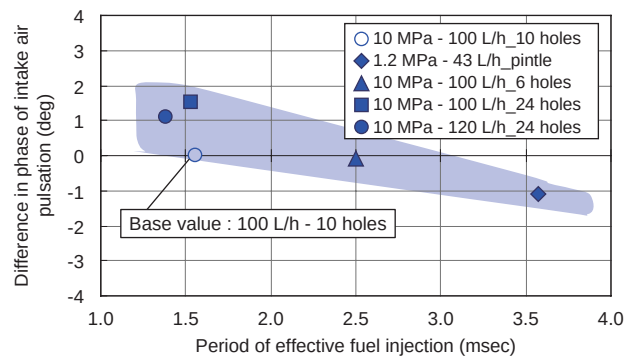


Fig. 4 Effect of injection time on difference in phase of intake air pulsation

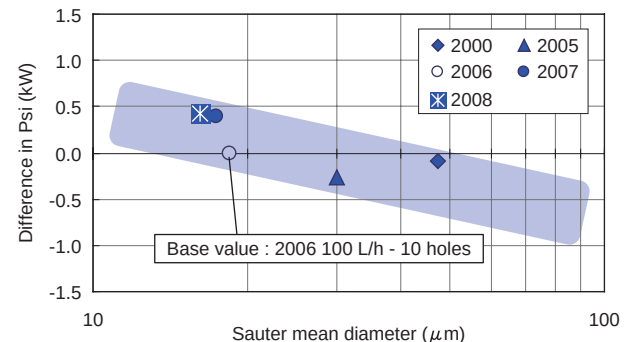


Fig. 5 Effect of droplet refinement on power

The relationship between penetration and the phase of intake air pulsation was also studied. As Fig. 8 shows, there is a peak in the intake air phase delay, indicating the existence of an optimum penetration for the achievement of increased intake air cooling efficiency. If the level of penetration is low, the spray will approach the center of the port due to the effect of the intake air. If the fuel is carried too high, the amount of fuel adhering to the walls of the port will increase.

A technological overview of the high-pressure fuel system based on the results of the analyses discussed above will be provided below.

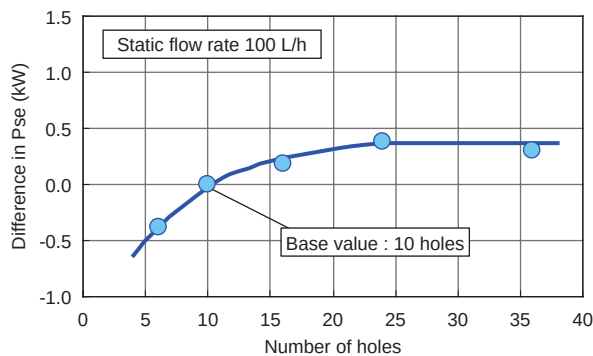


Fig. 6 Effect of number of holes on power

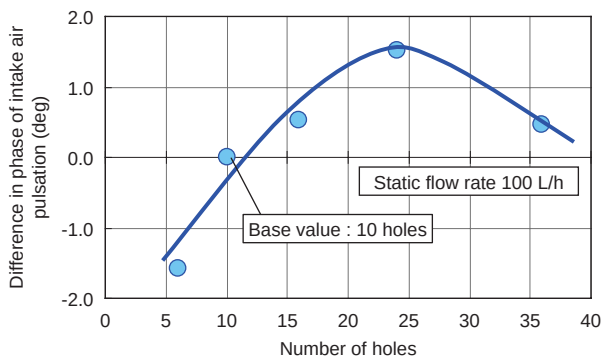


Fig. 7 Effect of number of holes on difference in phase of intake air pulsation

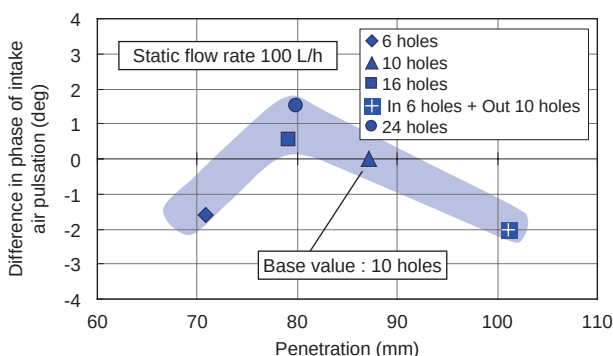


Fig. 8 Effect of penetration on difference in phase of intake air pulsation

3. Development of High-pressure Fuel Pump

In Honda's second Formula One era, the engine fuel supply system was composed of a gear pump producing a fuel pressure (PF) of 1.2 MPa, a fuel pressure regulator, and a side-feed injector, which supplied fuel from its side. At the commencement of engine development for Honda's third Formula One era, this basic configuration was carried over, with only the form of the injector being changed, to a top-feed type that supplied fuel from the upper section of the engine. Development and deployment of parts continued with consideration of their suitability to each model year engine.

Later, from 2005, the focus was shifted to the development of a system that helped to enable the achievement of increased intake efficiency and enhanced combustion by means of refining the fuel spray droplets from the injector and increasing atomization, and reducing the injection period, by increasing the pressure of the fuel supply system.

The achievement of a fuel pressure of 10 MPa was established as a target for the opening race of 2006. In the 2005 season, a commercial 5 MPa system had been used, and development time was concentrated on the achievement of 10 MPa.

In order to realize increased engine power by achieving a PF of 10 MPa, it would be essential to discard the previous gear pump and to conduct an in-house development of a high-efficiency and lightweight mechanical fuel pump that would be able to generate the necessary supply flow rate at high pressure. The reason for this was that at high fuel pressures, the efficiency of the previously used gear pump type would decline due to fuel leaks from the tips of the gear teeth and the gaps between the gear side faces, and it would be unable to transport the necessary amount of fuel.

To resolve this issue, the goal was initially to develop a gear pump configuration employing movable side plates to maintain fixed gaps between the gear side faces and moderate the volume of fuel leakage. However, this represented a technological challenge from the perspective of durability, raising issues such as the seizing of the sliding surfaces of the gear side faces. With the achievement of high fuel pressure and high efficiency as targets, efforts were therefore focused on the development of a new plunger piston-type fuel pump.

3.1. Overview of High-pressure Fuel Supply System

Figure 9 shows a diagram of the fuel system fitted in the fuel tank, incorporating a mechanical high-pressure fuel pump, a fuel pressure regulator, and primary and secondary electric fuel pumps. Formula One vehicles use explosion-proof fuel tanks (called "gas bags") manufactured from plastic liners. These tanks are fitted in the monocoque, and each year they are manufactured in conjunction with the monocoque, to dimensions that match the capacity of the monocoque. The collector tank helped to prevent abnormalities of suction of the gas bag fuel from arising in the electric pumps due to turning

or acceleration and deceleration G-forces, and pressurized the fuel to feed pressure for the mechanical high-pressure fuel pump. The collector tank was divided into two parts, a high-pressure collector tank and a low-pressure collector tank. Fuel from the gas bag was sent to the low-pressure collector tank by the primary electric fuel pumps positioned to the left and right on the floor of the gas bag. The fuel was then pumped from the low-pressure collector tank to the high-pressure collector tank by the secondary electric fuel pumps positioned on the floor of the low-pressure collector tank. The high-pressure collector tank employed a bladder, which was a variable volume pressurizing device using air pressure, to help ensure that the feed pressure of the fuel did not fall below the necessary level for supply to the mechanical high-pressure fuel pump. When no fuel was present in the high-pressure collector tank, the bladder swelled to fill the entire tank; when the tank was filled with fuel, the pressure of the fuel compressed the bladder. By means of this mechanism, the high-pressure collector tank could be constantly filled with fuel. The high-pressure collector tank was also provided with a pressure relief valve (PRV), which helped to ensure that the pressure in the tank remained at a constant upper limit. The bladder and the PRV stabilized the feed pressure to the mechanical high-pressure fuel pump, and helped to prevent cavitation when the high-pressure pump was taking in fuel at high temperatures.

3.2. Mechanical High-pressure Fuel Pump Configuration

Figure 10 shows an external view of the fuel pump produced by this development project. The initial specifications for the mechanical high-pressure fuel pump featured three units: a reduction gearbox to decelerate the pump against engine input, a gear pump to maintain the feed pressure for the plunger pump, and a plunger pump for high-pressure fuel supply. Later, in order to reduce weight, the reduction gearbox and the gear pump were integrated to produce a reduction gear pump. The rotational input from the engine was decelerated by the drive gears, while the gear pump supplied fuel. This helped to reduce the total length of

the pump by 30 mm and its weight by 340 g. The reduction ratios of the reduction gearbox and the reduction gear pump were optimized against engine speed in order to balance durability with good flow performance.

3.3. Selection of Pump Configuration

The pump was provided with a gear pump to help ensure stable feed pressure to the plunger pump. It was essential for the gear pump both to be small and lightweight and to function to prevent cavitation of the transported fuel when operating at high fuel temperatures in a circuit driving. A shape was designed that reduced pressure loss in the pump inlet port and an optimal gear pump thickness was set in order to reconcile the achievement of the desired supply flow rate with the realization of cavitation toughness. In addition, the optimum plunger piston size was selected and the resistance of the fuel channels was reduced in order to increase fuel transport efficiency, and a variety of modifications were made, including optimization of the stiffness of the pump body. As Fig. 11 shows, these measures resulted in the achievement of a level of total efficiency of 80% in the pump. As Fig. 12 shows, this total efficiency level was well beyond that of mass production pumps.

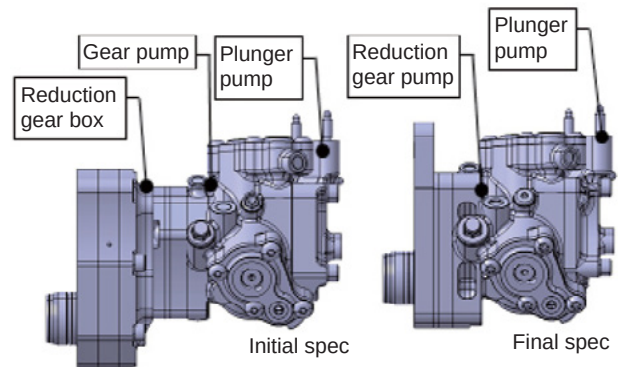


Fig. 10 High-pressure fuel pump

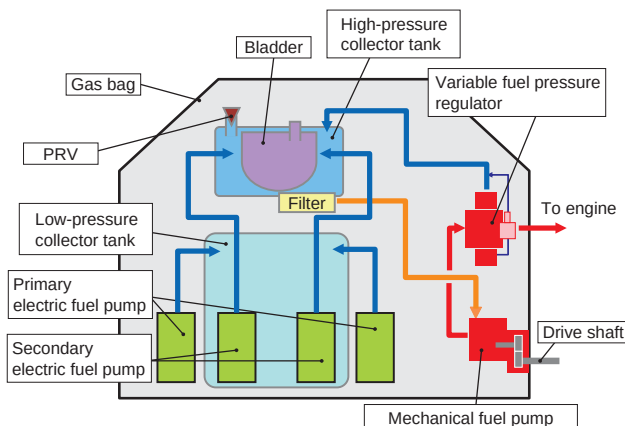


Fig. 9 Fuel system for Formula One engine

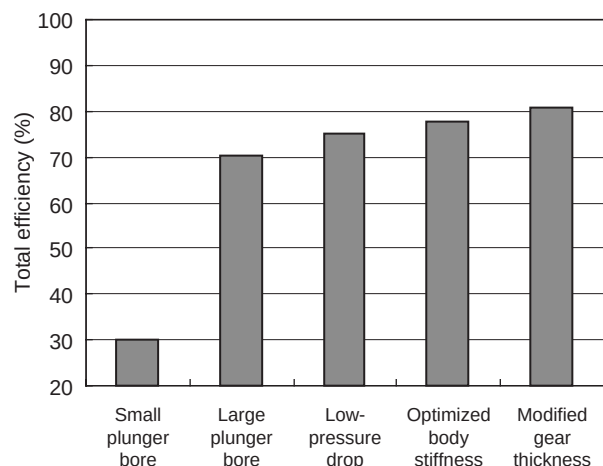


Fig. 11 Fuel pump characteristics

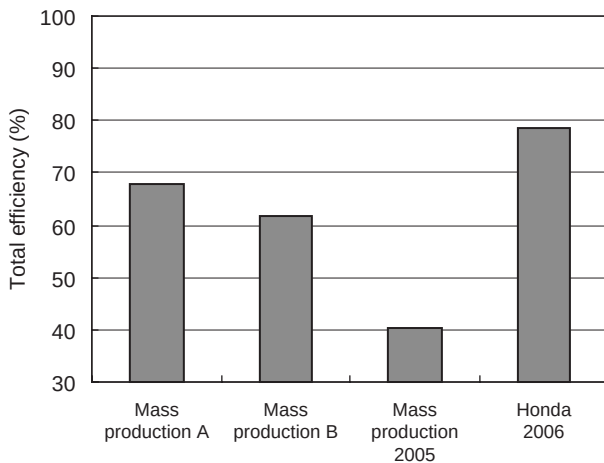


Fig. 12 Fuel pump characteristic comparison

4. Development of Variable Fuel Pressure Regulator

The aim of fuel supply system development for the 2006 season was to increase power by realizing a shorter fuel injection period through an increased injector supply flow rate. This presented the technological issue of the challenge of controlling the injector supply flow rate at high fuel pressures in the low load and idling ranges, ranges in which ultra-low supply flow rates are used. This led to the development of a variable pressure regulator using diaphragm back pressure control, which was able to reduce fuel pressure in the low load and idling ranges, and to increase fuel pressure in the high load range in order to maximize engine power, as a means of controlling the supply flow rate of the high-fuel-pressure, high-supply-flow-rate injectors.

4.1. Variable Pressure Regulator Configuration

Figure 13 shows the configuration and the operating principle of the variable pressure regulator. The variable pressure regulator was based on a pressure regulator using a diaphragm for return. The unit was provided with a back pressure spring chamber ("back pressure chamber" below) that applied back pressure to the regulator diaphragm. Forced application of fuel pressure to the back pressure chamber helped to enable the pressure difference of the diaphragm to be maintained at a constant level while the pressure adjustment function responded to higher fuel pressure. Fuel was supplied to the back pressure chamber via orifices in the fuel supply channels, and a fixed supply flow rate was maintained. A small needle valve regulator was used to hold the back pressure chamber fuel pressure constant. Because the small needle valve regulator controlled only an ultra-low supply flow rate, an orifice was positioned in front of it to help ensure that it was able to adjust pressure.

Pressure control in the variable pressure regulator operated as follows: When the regulator was switched to the low-pressure side, a solenoid valve was opened and the pressure was released from the back pressure chamber; pressure was adjusted using the pressure

difference of the diaphragm, as generated using spring power alone. When the regulator was switched to the high-pressure side, the solenoid valve was closed and fuel was supplied to the back pressure chamber.

4.2. Variable Pressure Regulator Performance

The main performance demand on the variable pressure regulator was responsiveness when switching fuel pressure between high and low pressures. If fuel pressure switching performance was unsatisfactory, the actual injector supply flow rate would become unstable, the engine combustion state would vary and air-fuel control would become challenging, resulting in unstable engine output. To avoid these issues, the responsiveness for switching from the low-pressure to the high-pressure side was set to within 500 ms, and the responsiveness of switching from the high-pressure to the low-pressure side was set to within 20 ms.

Switching responsiveness from the low-pressure to the high-pressure side was set via the size of the orifices in the fuel channels of the variable pressure regulator. Responsiveness from the high-pressure to the low-pressure side was set via the supply flow rate of the electronically-controlled solenoid valve used for pressure switching. The desired responsiveness was achieved through optimization of these specifications, helping to enable the achievement of a stable air-fuel ratio (Fig. 14).

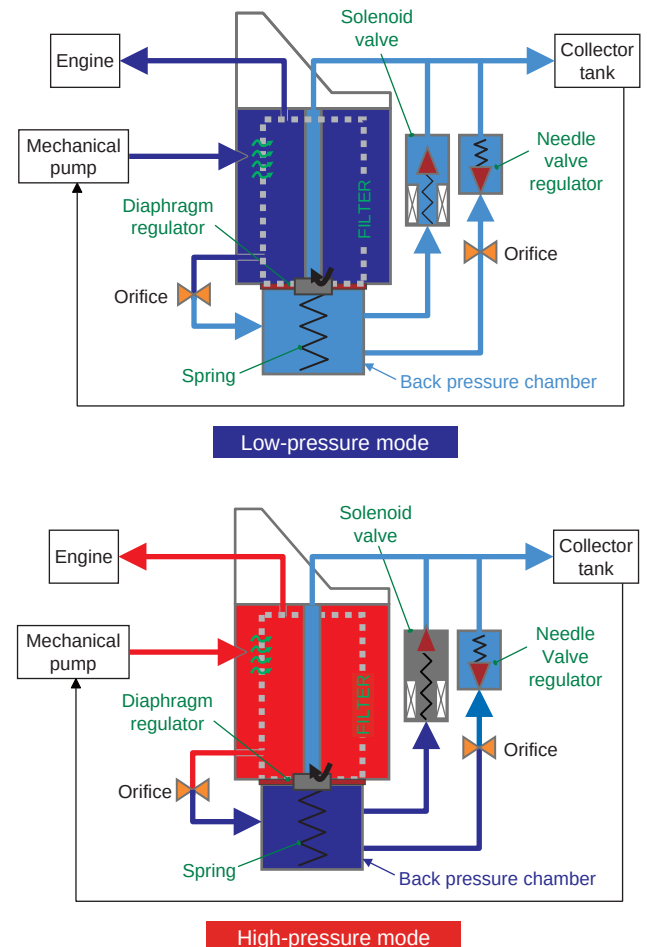


Fig. 13 Variable fuel pressure regulator system

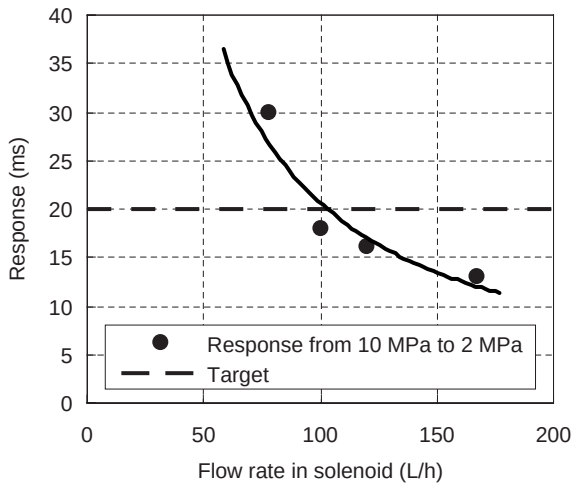


Fig. 14 Fuel pressure response characteristics

5. Evaluation of Durability of High-pressure Fuel System

The durability of the high-pressure fuel pump and the variable pressure regulator under actual operating conditions was verified. Unit tests were conducted to test durability at the pump speed frequency during mode operation. Dedicated pump, regulator, and injector unit test equipment that was able to reproduce circuit driving modes using an identical engine control computer to the computers employed in actual vehicles was used to conduct the evaluation.

The important points of focus in terms of fuel pump durability included body stiffness, lubrication performance, and the toughness of each constituent part; for the regulator they included body stiffness and the toughness of the plastic internal parts against swelling.

Focusing on these factors, sufficient durability was achieved to realize a maintenance interval making it possible to use the pump for multiple races.

6. Injector Development

6.1. Injector Specifications

As Table 1 shows, the injectors employed by Honda in races until 2008 can be grouped into five phases. This section will follow these groupings in discussing injector development.

6.1.1. Phase 1 (2000-2003)

Figure 15 shows the injector layout. The injectors were positioned at the top of the intake funnels (these will be termed “top injectors” below). Fuel was injected at a pressure of 1.2 MPa, and pintle-type single-hole nozzles produced a conical spray.

6.1.2. Phase 2 (2004)

To increase intake efficiency and responsiveness in the transient range in this phase, injectors were positioned close to the intake valves (“near valve injectors” (NI) below), to provide, with the top injectors,

Table 1 Injector type

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Year	'00 - '03	'04	'05	'06 - '07	'08
Inj layout	Top	Top + NI	Top + NI	Top	Top
Fuel pressure (MPa)	1.2	1.2	5	10	10
Static flow (L/h)	43	43 (NI:33)	55 (NI:55)	78, 100	100
Hole type	Pintle	Pintle (NI:Multi)		Multi	Multi
Number of holes	–	(NI:6)		6, 10, 24	24

two injectors per cylinder. Because the NI were positioned close to the valves, the use of multi-hole nozzles helped to enable the realization of sprays from two directions directly aimed at each port. Because it was necessary to accurately control an ultra-small flow, the supply flow rate for the NI was set lower than that of the top injectors.

6.1.3. Phase 3 (2005)

In this phase, a system using a fuel pressure of 5 MPa was introduced in order to boost engine performance by increasing the atomization of the spray through the use of high-pressure fuel injection. The Honda-made NI was modified for high fuel pressure use, but commercial units were employed for the top injectors, pump, and regulator.

6.1.4. Phase 4 (2006-2007)

The Phase 3 NI was modified for use with a fuel pressure of 10 MPa, and was employed in races. From 2006, regulations set an upper limit of 10 MPa for fuel pressure, and also stipulated that only one injector could be used per cylinder. Given this, development was conducted to achieve the effect of the NI using only a top injector, and the effect of the spray on engine response was added as spray selection criteria in the injector spray development process.

To boost engine performance, a development program was conducted during the season to help enable the use of a shorter injection period by increasing the injector supply flow rate and generating further atomization of the spray by increasing the number of injector holes. The

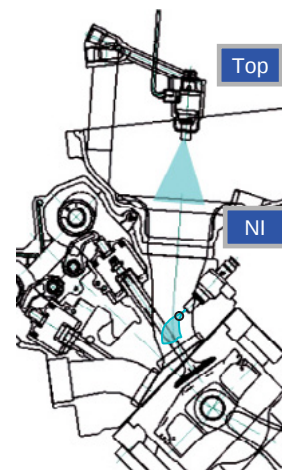


Fig. 15 Injector layout 2

final spray configuration in Phase 4 was a conical spray using 24 holes. In addition, because the fuel pressure regulations had increased the importance of the spray characteristics, research on new methods of evaluation of these characteristics and study of next-generation injector specifications was commenced.

6.1.5. Phase 5 (2008)

Using spray measurement and evaluation methods developed in the previous year, the effect of differences in spray on actual engine performance was analyzed, and a concept of the optimum spray was formulated.

This concept was reflected in a new injector design, and the injector was employed in races from the opening race of the 2008 season. Regulations had prohibited any changes to injector specifications that would boost output performance, but modifications were made as needed during the season to increase reliability.

The next section will discuss the Phase 5 specifications, the final injector specifications used by Honda in Formula One.

6.2. Injector Development Concept

6.2.1. Reduction of size and weight

A reduction in the size of the injectors would reduce their weight, increase the degree of freedom of layout, and also help to enable the delivery pipes and other parts to be reduced in weight. The achievement of weight savings in the injectors positioned at the top of the engine and in fuel system-related parts would contribute to lowering the center of gravity of the engine.

6.2.2. Modification of supply flow rate characteristic

In the high engine speed environment (maximum: 19000 rpm) of a Formula One engine, it is necessary to promote the dispersion of the fuel spray and achieve an intake air cooling effect by injecting a large quantity of fuel in a short time period.

In addition, stable injection is also necessary when ultra-low quantities of fuel are injected, when the engine is idling or off-throttle. The achievement of increased responsiveness in the injector needle valves was focused on in order to achieve a fuel spray characteristic that satisfied these performance demands.

6.2.3. Modification of spray characteristic

A balance between the form angle, droplet diameter, dispersion, and penetration is necessary for the spray characteristic. However, increased atomization is in a trade-off relationship with dispersion and penetration, and an increase in atomization will cause a decline in dispersion and penetration, and vice versa. The previous injectors had reached the limit values for each parameter, making the realization of enhanced performance an urgent issue.

Against this background, the regulations had established an upper limit for fuel pressure. In order to efficiently utilize the energy of the fuel pressure in the spray characteristic, the actual fuel pressure on the holes (the hole plates) in the injectors (termed “plate feed

Table 2 Injector specifications 1

Year	2007	2008
Length (mm)	57	48
Diameter (mm)	20	16
Weight (g)	65	38
Number of coil windings	268	100
Coil resistance (Ω)	2.8	1.0
Operating current (A)	Peak: 2.4 Hold: 0.6	6.0

pressure” below) was focused on (Fig. 16). The reduction of fuel pressure loss in the injectors increased the plate feed pressure, helping to enable the realization of a spray characteristic equivalent to that of an actual increase in fuel pressure.

6.3. Developed Injector Technologies and Performance

6.3.1. Reduction of size and weight

Figure 17 shows an external view of an injector. A new magnetic material developed for use in the injector (cobalt steel) was employed to reduce the size and weight of the units. In addition, the structure of the needle valves was modified, helping to enable the total length of the valves to be reduced. Because the size of the injectors was determined by the number of coil windings, the number of windings was also reduced.

However, reducing the number of coil windings would result in a decline in magnetic attraction. The magnetic circuits were therefore optimized and drive current increased in order to increase attraction.

Table 2 shows the size of the injectors and the coil specifications.

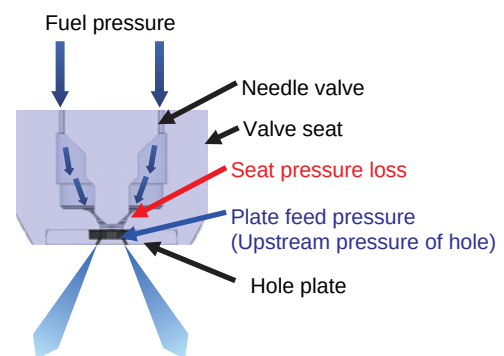


Fig. 16 Injector internal fuel flow (2007 model)

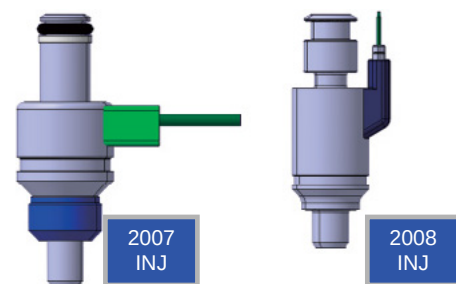


Fig. 17 Injector body shape

6.3.2. Supply flow rate characteristic

Without variable fuel pressure control, the 2007 injectors were not able to conduct stable fuel injection from idling to wide-open throttle. A development project was therefore initiated to produce a new injector that would be able to inject fuel across the operating range under high pressure. In order to realize this goal, the weight of the needle valve (a movable part) was reduced; the magnetic characteristic was enhanced by modifying the magnetic materials and magnetic paths; the rise in magnetomotive force was increased by the increase in the rise in current achieved by reducing the number of coil windings (reducing the resistance value); and the responsiveness of the needle valve rise was enhanced by means of the increase in the magnetic attraction of the valves achieved by increasing the drive current. The spring set load could also be increased by the amount of the increase in magnetic attraction, helping to enable an increase in needle valve fall responsiveness.

In addition, the drive current waveform was reexamined and the linearity of the fuel supply flow rate against current was enhanced. As a result, when the injector spray characteristic was equivalent to the 2007 model, the injector was able to inject fuel at high pressure across the entire operating range.

However, the needle valve stroke and the diameter of the valve seats were increased in order to boost the plate feed pressure, with the aim of enhancing the spray to increase power. This made control of the ultra-low supply flow rates at low loads and in the idling range a challenge, and as a result, the use of variable pressure control was continued.

This was the result of a comparative examination of the effect on engine performance of enhancing the spray characteristic and the effect on actual vehicle performance (weight savings) of discarding the variable pressure control system. It was determined that the

Table 3 Injector specifications 2

Year	2007	2008
Static flow (L/h)	100	100
Angle of spray (deg)	53	53
Seat diameter (mm)	ϕ 1.30	ϕ 1.48
Valve stroke (mm)	0.10	0.15
Plate thickness (mm)	0.4	0.2
Number of holes	24	24
Hole diameter (mm)	0.100	0.090

enhancement of the spray characteristic was a more important consideration.

6.3.3. Spray characteristic

The needle valve stroke and the diameter of the valve seats were increased in order to reduce the pressure loss resulting from the squeezing of the valves, resulting in increased plate feed pressure. Table 3 shows the points that were modified, and Fig. 18 shows the configuration of the injectors.

In addition, the fuel flow was modified by optimizing the shape of the internal fuel channels and employing spherical valve seats. These modifications increased plate feed pressure from 4.7 to 8.9 MPa at a fuel pressure setting of 10 MPa.

The enhancement of spray performance (droplet diameter, penetration, diffusion) helped to enable the achievement of a good balance between these parameters, which are in a trade-off relationship. The 24-hole conical spray configuration that was judged to be optimal in terms of vehicle performance based on the analysis in Section 2.1. was adopted (Fig. 19).

With regard to atomization, an average droplet diameter (SMD) of approximately 17 μm was achieved.

7. Conclusion

(1) Development of high-pressure pump and variable pressure regulator

A pump efficiency of 80% was achieved through a variety of measures, including reduction of pressure loss in the pump inlet port and optimization of the size of the plunger pistons.

In addition, the employment of a variable pressure regulator helped to enable the realization of high-supply-flow-rate injection, resulting in increased engine output and stable injection of ultra-low fuel supply flow rates at low loads.

(2) Development of high-pressure injectors

The use of new magnetic materials and the modification of the injector configuration and the drive current helped to enable the injectors to be reduced in size.

With regulations stipulating an upper limit on fuel pressure, the development aimed to increase combustion efficiency by means of atomization of the spray; reduction of internal pressure loss in the injectors helped to enable the achievement of a spray characteristic that

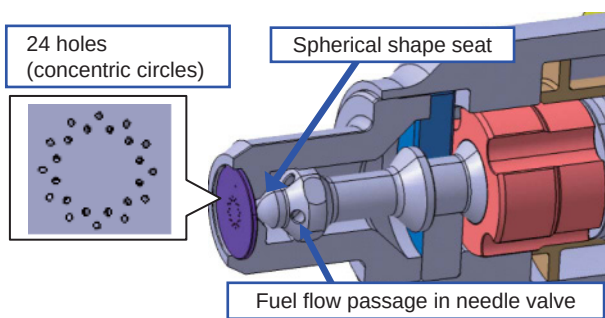


Fig. 18 Injector internal structure (2008 model)

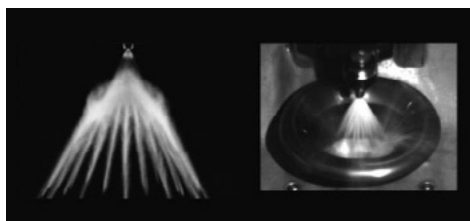


Fig. 19 Atomization achieved by 24-hole injector

produced a performance enhancement equivalent to that of an actual increase in fuel pressure.

(3) Engine performance

Increasing fuel pressure helped to enable an increase in the maximum injector supply flow rate; the resulting shorter injection period promoted dispersion of the fuel spray, and an intake air cooling effect was obtained. In addition, increased atomization promoted greater mixing of the intake air and the fuel, enhancing combustion efficiency. As a result of these measures, fuel system development produced an increase in power of approximately 15 kW against previous levels at the commencement of Honda's third Formula One era.

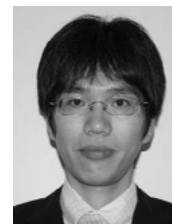
■ Author ■



Tetsuya TANAHASHI



Kazuji ONO



Masanori HAYAFUNE



Yosuke SAWADA



Atsushi SHIMIZU