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QUICK RESPONSE FUEL INJECTOR FOR DIRECT-INJECTION GASOLINE ENGINES

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ABSTRACT

We developed a new injector for direct injection gasoline engines that reduce the exhaust emissions and help to reduce fuel consumption. The newly developed actuator in this injector has two features. One is a bounce-less valve closing mechanism, and the second is quick-response moving parts.

The first feature, the bounce-less valve closing mechanism, can prevent ejecting a coarse droplet, which causes unburned gas emission. The new actuation mechanism realizes the bounce-less valve closing. We analyzed the valve motion and injection behavior.

The second feature, the quick response actuator, achieves a smaller minimum injection quantity. This feature assists in reducing the fuel consumption under low load engine conditions. The closing delay time of the needle valve is the dominant factor of the minimum injection quantity because the injection quantity is controlled by the duration time of the valve opening. The new actuator movements can be operated with a shorter closing delay time. The closing delay time is caused by a magnetic delay and kinematic delay.

A compact magnetic circuit of the actuator reduces the closing delay time by 26%. In addition, the kinematic delay was improved when the hydraulic resistance was reduced by 9%.

As a result, the new injector realizes reduction of the minimum injection quantity by 25% compared to a conventional injector.

INTRODUCTION

Improving the fuel consumption and reducing the hydrocarbon (HC) emission exhaust are important issues for spark-ignition engines. A direct injection (DI) fuel system is one way to improve the fuel consumption [(1)]. A fuel injector is a key component in determining the emission and fuel efficiency performance of DI engines [(2)(3)]

One of the causes of HC emissions is coarse droplets. For the DI system, the injector nozzle makes the fuel spray directly into the combustion chamber. Therefore, the spray droplets should be finely atomized to promote the evaporation of the fuel before ignition. However, at the end timing of the injection, coarse droplets called “post injection” still remain. This is caused by the valve needle bounce at the closing moment. The DI injector should prevent this post-injection.

A small minimum injection quantity is required to obtain an acceptable fuel consumption level. The injection quantity is generally controlled by the duration time of the input pulse. However, when the pulse is too short, the quantity is significantly non-linear against the pulse duration. This non-linearity makes a minimum controllable injection quantity difficult to achieve. The injection quantity linearity depends on the response speed of the needle valve.

Therefore we have to develop a new injector with quick response, and one without needle bounce. (The structure has been disclosed by patent documents [(4)(5)(6)(7)(8)].) This paper describes the detail of the mechanism of new injector design.

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INJECTOR MECHANISM

Figure 1 shows a schematic of a conventional DI injector and our newly developed one. Basically, the DI injector is an ON-OFF type solenoid valve. The valve opens when the coil is energized. The injection quantity is related to the valve opening time and is controlled by the input pulse duration.

The moving parts of the injector include an anchor and a needle valve. The needle valve seals the fuel when the needle valve is in contact with the valve seat. The anchor generates magnetic-force and transmits it to the needle valve.

In addition, the moving part should have a function to prevent needle bounce. The newly developed injector has a simple actuation mechanism that eliminates needle bounce. The mechanism reduces the number of the moving parts compared to the conventional one.

Figure 2 is an enlarged view around the moving parts. In the conventional design, we adopted a “dynamic damper” to prevent needle bounce, but this requires damping mass and leaf spring parts.

In the new design, the needle-valve and moving anchor are separated instead of being a dynamic damper. This structure eliminates the mass and springs.

The conventional one requires five parts for the bounce prevention mechanism, but the new one requires only three.

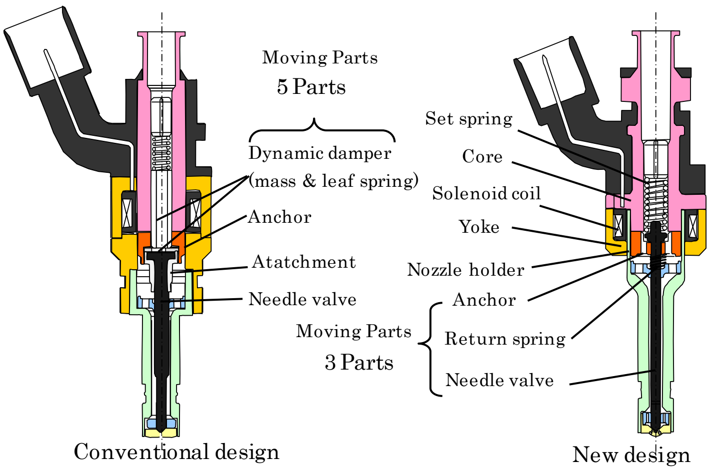

Figure 1 Schematic image of DI injector

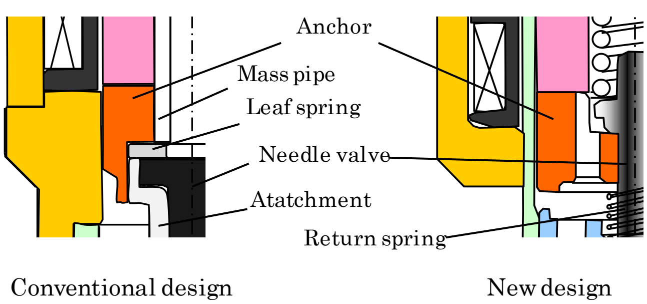

Figure 2 Enlarged view of moving parts

OPERATION AND BEHAVIOR

Figure 3 presents a graphic explanation of the opening motion of the moving parts. In the closing state, the solenoid coil is not energized so the needle valve remains in contact with the seat. When an electric current is supplied, the magnetic core generates magnetic flux through the anchor, and magnetic force is received. When the magnetic force becomes greater than the spring set load, the needle valve begins to lift. After the anchor makes contact with the core, the needle valve opens.

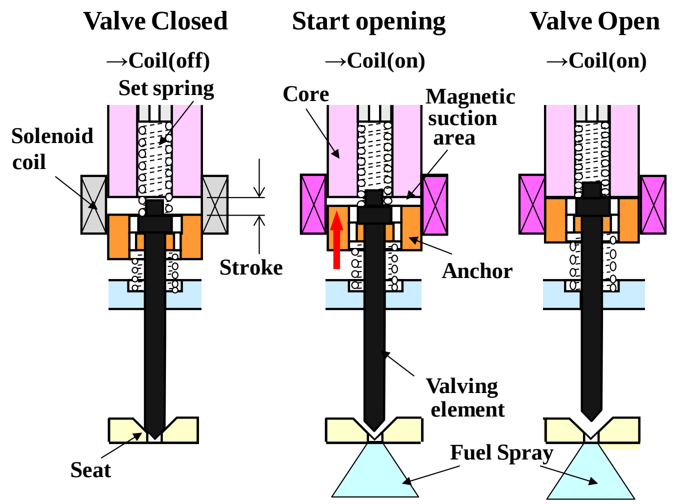

Figure 3 Valve opening operation

Figure 4 shows the valve closing behavior. When the current supply stops, the magnetic force disappears and the anchor and needle valve start to close. The moving mass is the sum of the anchor and the needle masses.

After the needle comes into contact with the seat element, the needle valve cannot close. However, the anchor can continue to move independently. The needle valve experiences bounce motion but the set-spring load works only for the needle valve because the mass of the needle valve is separate from the anchor. The kinetic energy of the anchor can dissipate into fuel around the anchor. Therefore, the needle valve bounce is lessened, and quickly reaches the closing state. This is the bounce prevention mechanism.

This effect is shown in Figure 5, which is a calculation result. The calculation was based on 1-dimensitonal Newtonian mechanics, and it includes hydraulic damping.

The needle bounce height has been reduced by the bounce prevention mechanism. Figure 6 is the confirmed result from the spray observation. No post-injection was observed in the newly developed injector.

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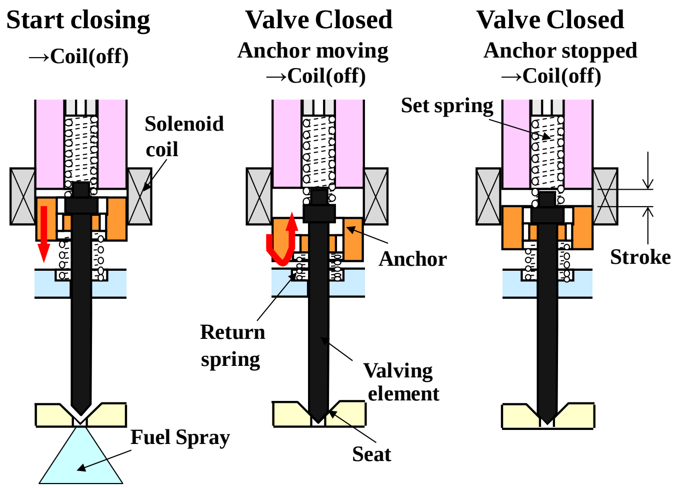

Figure 4 Valve closing behavior

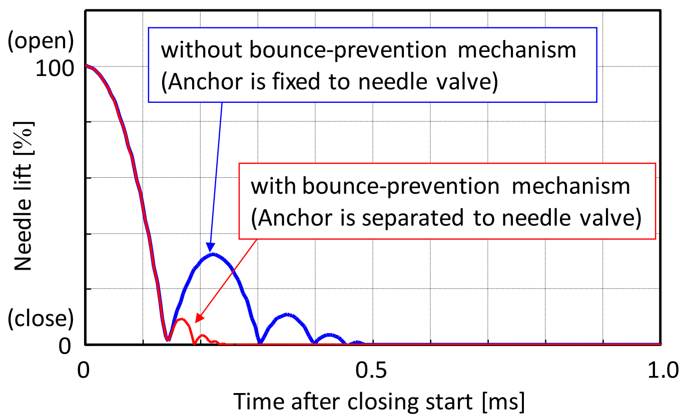

Figure 5 Bounce-prevention effect (simulation)

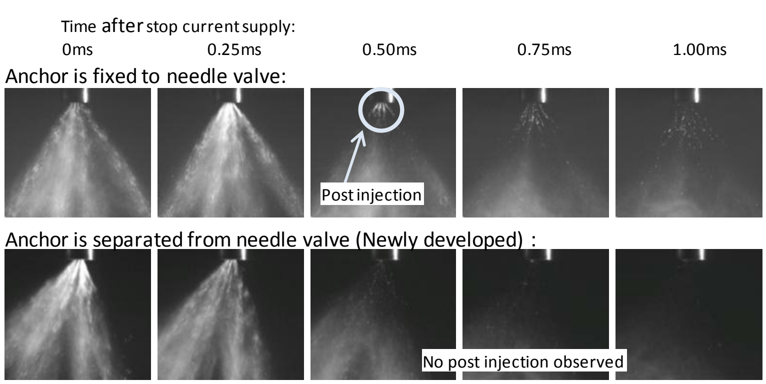

Figure 6 Bounce-prevention effect (observation)

INJECTION QUANTITY AND VALVE MOTION

This section explains the relation between the injection quantity and valve motion, and how to reduce the injection quantity. Figure 7 shows the characteristics of the injection quantity against the input pulse duration. We can see a linear region in the long pulse and non-linear region at a short pulse width. The linear region can be used for a practical engine. The non-linear region may cause inaccuracies at lower fuel quantities, so it is impractical. The injector contains a value of minimum controllable injection quantity.

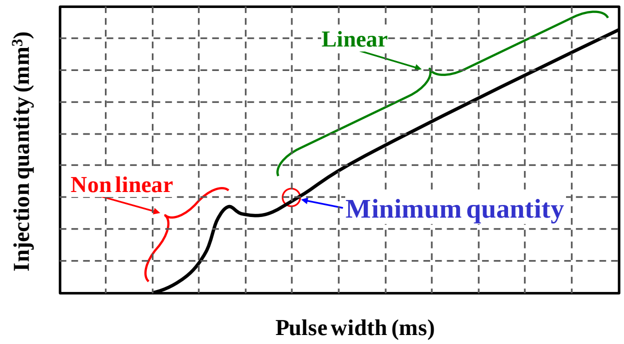

Figure 7 Injection quantity characteristics

In general, the valve opening duration increases when linearly lengthening the pulse width. However, when there is a short pulse, the valve cannot reach the full lift height. Therefore, the valve opening duration is not proportional to the pulse width. This is the cause of the non-linearity.

Figure 8 shows the dominant factor for the minimum injection quantity. Generally, the needle valve motion should encounter a time delay from the input pulse so that the duration of the valve opening cannot reach zero. The minimum injection quantity is determined by the duration of the opening at the minimum pulse width. Therefore, the closing time delay is the dominant factor.

The closing delay time should be reduced to obtain a smaller minimum injection quantity. The cause of the closing delay time is the magnetic delay and kinematic delay. It is important to reduce these time delays.

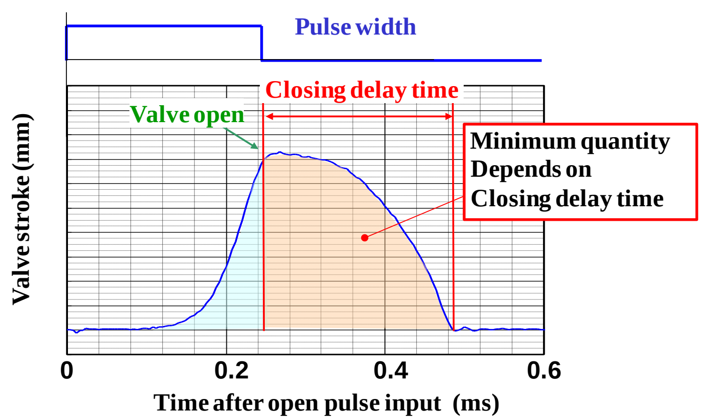

Figure 8 Valve motion for minimum injection quantity

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MAGNETIC CIRCUIT IMPROVEMENT

An injector needs a certain target level of magnetic force to open the needle valve. The magnetic force is brought by the magnetomotive-force, which is expressed in Ampere-turns (AT). The magnetomotive-force depends on the electric current supply and the turn number of the coil. Therefore, a large magnetomotive-force requires a longer duration of time to reach the target level. To obtain a faster magnetic force response, it is important to reduce the magnetomotive-force level.

Basically, the magnetic force F and magnetomotive-force ni are described as

$$F = \frac{B^2 S}{2\mu_0}$$

$$H_0 = \frac{ni}{l}.$$

The magnetic force F is proportional to the power value of the magnetic flux density B. Therefore, to obtain a sufficient amount of magnetic force, the input magnetic field H_0 should be large because the magnetic field H_0 induces flux density B. (Usually the relation between B and H is given as a B-H curve.)

The H_0 is proportional to the magnetomotive-force ni, but is inverse proportional to the length of the magnetic circuit. To obtain a larger H_0 with a small ni, the length l should be short.

Therefore, we redesigned the magnetic circuit to be more compact.

Figure 9 shows the effect of a compact magnetic circuit. The conventional design of a magnetic circuit requires a ni= 320 [AT] to reach the target level of magnetic force, but the new design requires only a ni= 230 [AT].

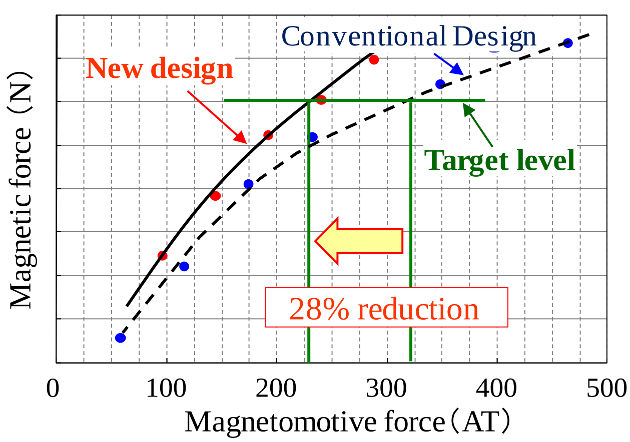

Figure 9 Magnetomotive-force reduction to reach target level

The new design can be driven by small turns in the coil so that the Ampere-turns requirement can be reduced. Therefore, the magnetic response should be faster. Figure 10 shows the improvement in closing delay time. We achieve a 26% reduction in closing delay time using our compact magnetic circuit.

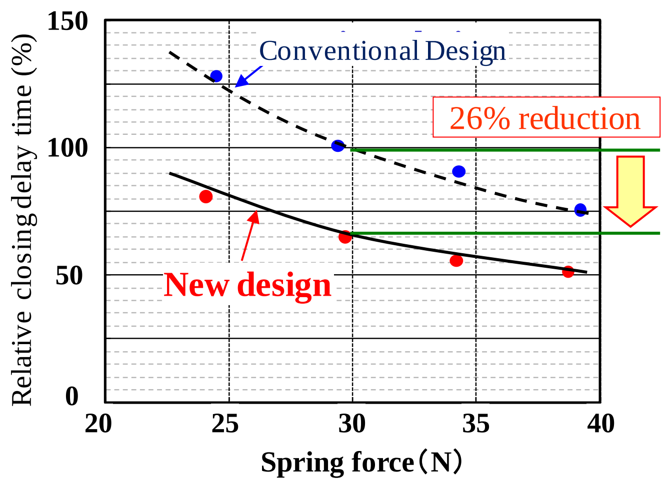

Figure 10 Improvement in closing delay time

REDUCTION OF HYDRAULIC RESISTANCE

Hydraulic resistance is one of the more important factors for shortening the closing delay time. Figure 11 shows the effect of the hydraulic effect when closing.

Under dry conditions, the time delay is determined only by the magnetic delay. When there is fuel around the moving parts, the closing delay time becomes longer due to the hydraulic resistance.

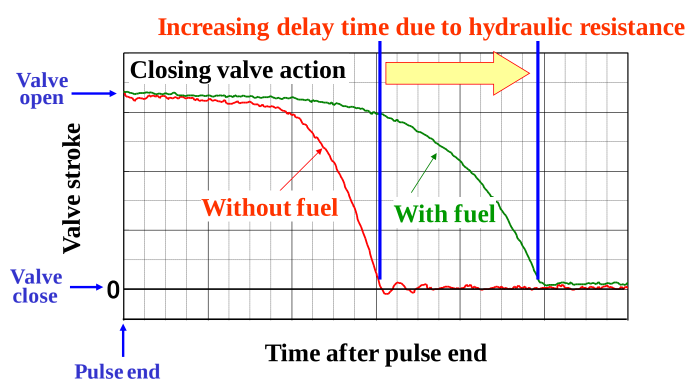

Figure 11 Hydraulic effect against closing delay time

Figure 12 illustrates the fuel flow around the moving parts. At the moment the anchor moves downward, the fuel under the anchor must flow into the gap between the anchor and the core.

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This movement of fuel causes a pressure drop between the gap and bottom of the anchor. Therefore, hydraulic resistance is induced.

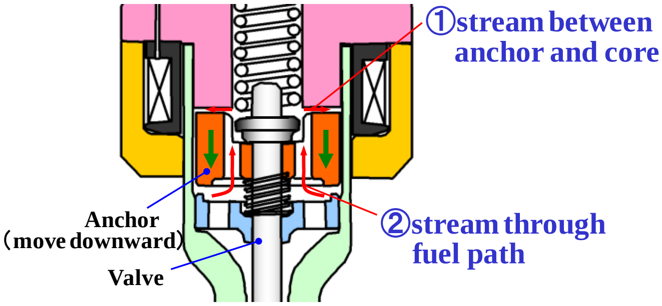
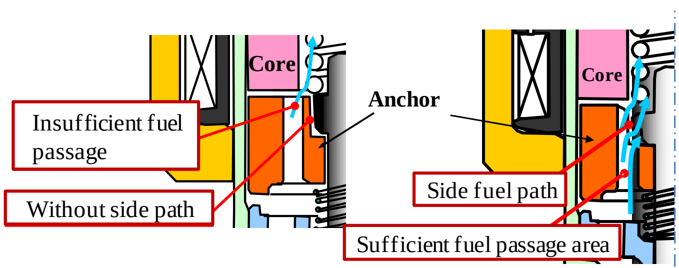


Figure 12 Hydraulic flow around moving anchor

A sufficiently-sized fuel passage is needed to reduce the resistance. Figure 13 shows a comparison between the initial and improved designs of the fuel passage.

In the initial design of the anchor, the fuel passage area was a cylindrical hole. In this design, the inlet of the passage is blocked by the opposing surface of the magnetic core. This fuel passage is insufficient because the gap between the core and the anchor is narrow. A narrow inlet area induces a lot of hydraulic resistance.

We redesigned the shape of the anchor to obtain a sufficiently-sized fuel passage. We made a side path at the passage inlet so that the fuel can flow through the side path into the passage hole. The fuel passage at the inlet is extended by the side path, and therefore, the hydraulic resistance is reduced.



(a) Initial design (without side path)
(b) Improved design (with side path)

Figure 13 Fuel passage of anchor

Figure 14 shows the effects of this improvement due to the reduction in hydraulic resistance. The vertical axis indicates the elongation of the closing delay time due to the hydraulic resistance. The elongation was improved by approximately 50% at a fuel pressure of 5 MPa. This improvement corresponds to 9% of the total closing delay time.

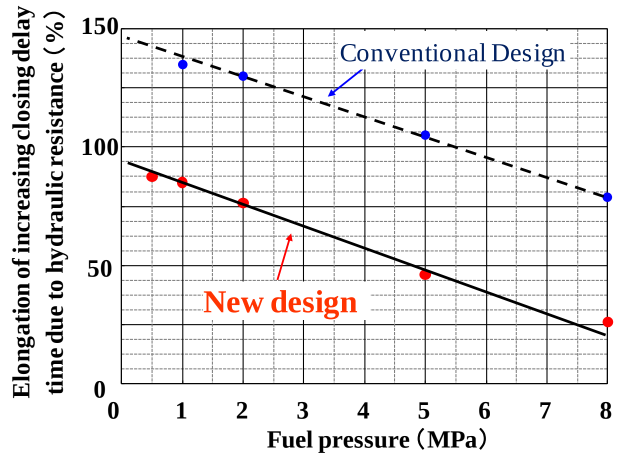


Figure 14 Fuel passage of anchor

TOTAL IMPROVEMENT OF INJECTION QUANTITY

The newly developed injector has reduced the closing delay time. Figure 15 shows the experimental results of a comparison of the closing delay time between the new design and the conventional one.

The improvement as a result of magnetic circuit optimization was 26%, and due to the hydraulic resistance was 9%. The new design improved the closing delay time by 35%.

The closing delay time corresponds to the minimum injection quantity. Figure 16 shows the characteristics of the injection quantity.

The linear region was extended, and the minimum injection quantity was reduced. A 25% improvement was thus observed.

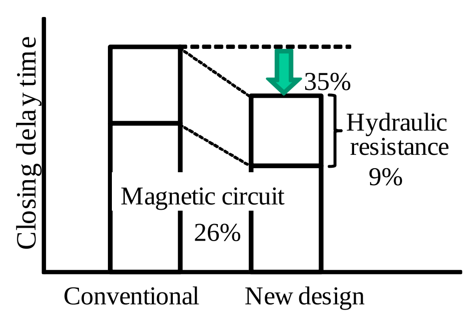


Figure 15 Total reduction of closing delay time

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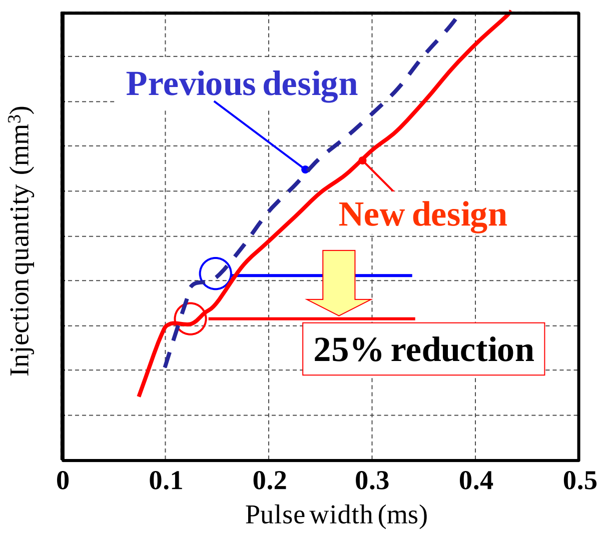

Figure 16 Improvement of injection quantity characteristics

SUMMARY

We have developed a new injector, and the following has been accomplished.

1. The anchor being separated from the needle valve can prevent post-injection.
2. The new compact magnetic circuit realizes 28% reduction of magneto-motive force to obtain sufficient level of magnetic force.
3. The new magnetic circuit reduces the closing delay time by 26%.
4. The fuel passage of the anchor has been extended by creating a side path to the passage hole.
5. The newly designed anchor with the fuel passage can reduce the closing time delay by 9% due to the hydraulic resistance.
6. Finally, the newly designed injector has reduced the minimum injection quantity by 25%.

NOMENCLATURE

F	:	Magnetic force [N]
S	:	Area of anchor surface [m^2]
B	:	Magnetic Flux [T]
H	:	Magnetic Field [A/m]
μ_0	:	Magnetic permeability of vacuum [A/m^2]
n	:	Turn number of coil [Turns]
i	:	Electric current [A]
(ni	:	Magnetomotive-force [AT])

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