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Development of a New Injector in Gasoline Direct Injection System

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ABSTRACT

The required fuel spray characteristics, controlled fuel pressure, and injector installation configurations in gasoline direct injection differ among manufacturers. As a result, there are currently a variety of injector types and configurations being proposed by many different component manufacturers.

This paper proposes a new injector design that both enables high fuel pressure operation by utilizing a highly efficient electromagnetic valve using a composite magnetic material for the injector actuator, and increases manufacturing productivity while also meeting the requirements of each engine manufacturer by simplifying the construction of the injector.

INTRODUCTION

Recently, a great number of engine manufacturers, taking the need to protect the global environment and prevent global warming into consideration, have been paying attention to gasoline direct injection engine characteristics which have the potential to improve fuel economy and in turn reduce emission of CO_2. These benefits have prompted makers to research the gasoline direct injection engine, and the diffusion rate in the market has been increasing year by year.

To ensure the predominance of the gasoline direct injection engine, each engine manufacturer is aiming at expansion of the range of stratified combustion, from low load to high rpm, and at generation of higher power under high load by homogenizing combustion.

However, as controlled fuel pressure, spray configuration, and installation configuration in the engine differ according to engine manufacturer, there are a variety of injector types and configurations being proposed by a number of component manufacturers[1].

In order to expand the use of direct injection systems in the future, there is a pressing need to develop an injector which increases manufacturing productivity while meeting those requirements.

CONCEPT OF THE NEWLY DEVELOPED INJECTOR

We started development of an injector that would satisfy the injector performance requirements that are currently being proposed by many manufacturers of engines.

The concept of the development is:

1. Small size and improved dynamic flow range with higher pressure,
2. Flexibility to satisfy injector performance requirements by replacing parts,
3. Raised manufacturing productivity by simplification of the construction of the injector.

In developing a next generation injector, it is necessary to increase the productivity of manufacturing the injector by simplifying the shape of the parts and designing them so that they will fit in a construction such that assembly can be performed from one direction.

We propose a next generation direct injection injector configuration that combines functional design with production engineering.

FEATURES OF THE NEWLY DEVELOPED INJECTOR

Figure 1 shows the configuration of our current production injector and of the newly developed injector.

Newly developed injector uses the sleeve of the composite magnetic material as the key part. The composite magnetic material will be explained in detail later. Using this material, we were able to design an injector which increases the productivity of manufacturing the injector by simplifying the shape of the parts and designing them so that they will fit in a construction such that assembly can be performed from one direction.

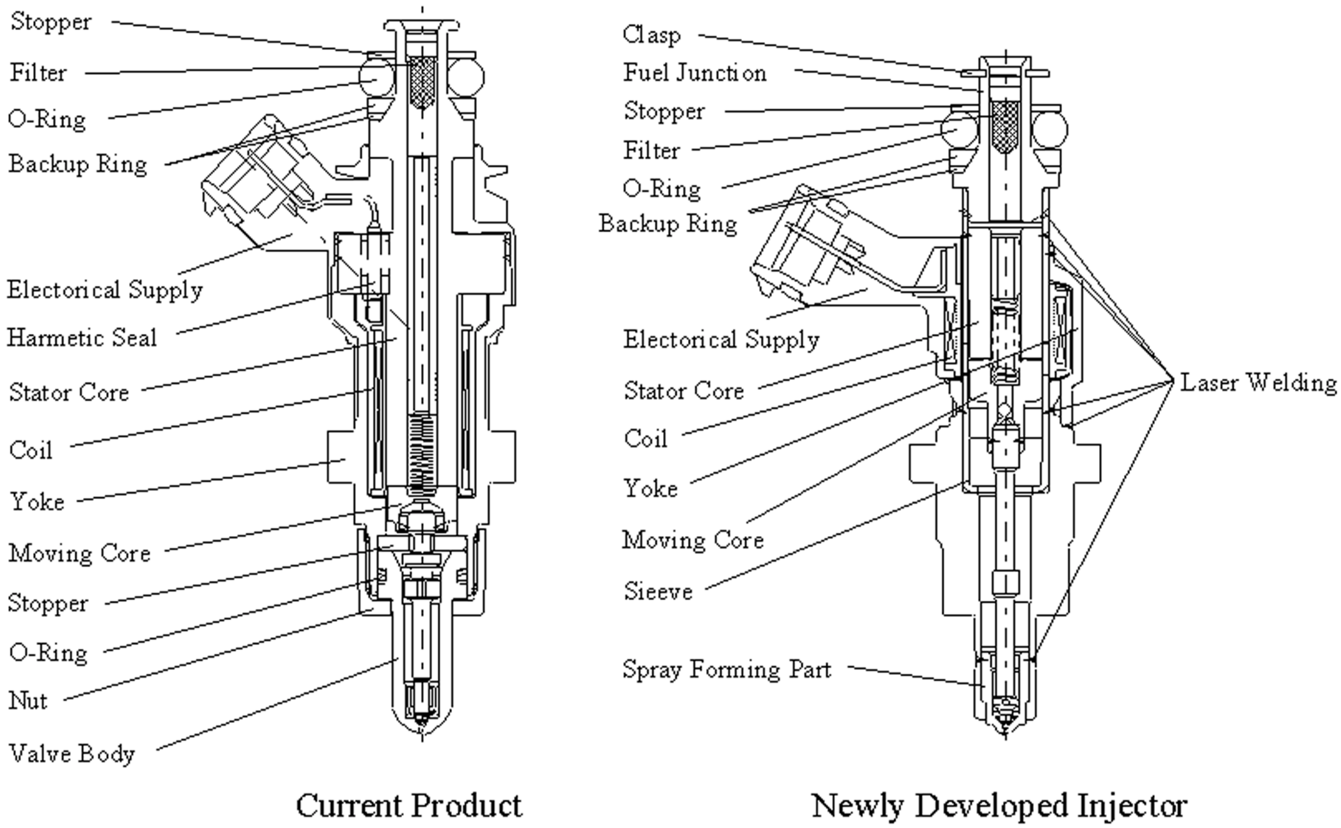

Figure 1. Current Production and Newly Developed Injectors

Table 1. Comparison of Characteristics

	Current Production Type	Newly Developed Type
Fuel Pressure	8 - 13 MPa	6 - 15 MPa
Static Flow Rate @12 MPa	660 cm^3/min	840 cm^3/min
Dynamic Flow Rate	max. 55 mm^3/stroke @13 MPa	max. 78 mm^3/stroke @15 MPa
	min. 5 mm^3/stroke @8 MPa	min. 5 mm^3/stroke @6 MPa

Table 1 shows the characteristics of the current production injector and of the newly developed injector.

Compared to the current production injector, the newly developed injector has a wider fuel pressure range and expanded dynamic flow range. Generally, static flow can be controlled by changing the nozzle size, and if the maximum injection quantity increases then so must the minimum injection quantity. However, because the newly developed injector has a high output magnetic valve, static flow rate can potentially be increased 30% higher compared to the production injector, without increasing the minimum injection volume.

The structural characteristics of the newly developed injector are explained below.

FUEL SEALING – Most conventional injectors use an O-ring seal as the internal fuel seal. Indeed, our current production injector uses an O-ring seal and a hermetic seal to keep the fuel from leaking out. However, for the newly developed injector, laser welding both fixes the parts and keeps the fuel from leaking out.

ELECTRICAL SUPPLY – The following is an outline of the process for the current production injector, throughelectric connector molding.

First, the bobbin is molded on the stator core, the terminals are fixed on the bobbin, and the wire is wound on the bobbin. After winding the wire, the stator core is inserted in the yoke and fixed by laser welding. With the newly developed injector, however, the coil and electrical supply are constructed in a separate module, inserted over the sleeve, and fixed to the sleeve by laser welding from both sides. The electric coil module is completely separated from the fuel, thereby eliminating the need for the seal structure.

STATIC FLOW ADJUSTMENT – Static flow of injectors is determined by flow at the nozzle and the seat when the needle is lifted. In the newly developed injector, needle lift is determined by precisely pressing a stator core into a sleeve. After the lift is adjusted, the stator core is fixed with spot welding.

SPRAY FORMING PART – Figure 2 shows the configuration of the spray forming part.

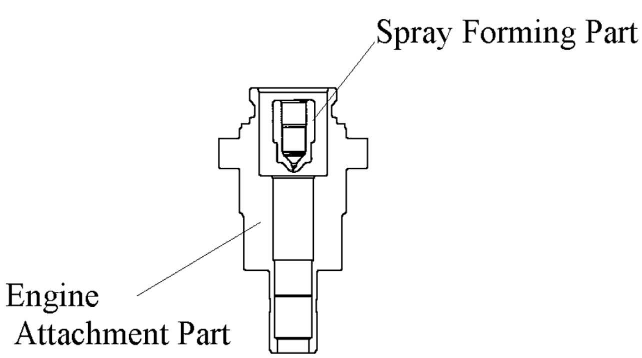

Figure 2. Spray Forming Part

The spray configuration required differs according to the different combustion concepts of each engine manufacturer. Here, the spray forming part is constructed separately so that those requirements can be met with only the replacement of the spray forming part.

ENGINE ATTACHMENT PART – Figure 3 shows the installation of the injector in the engine.

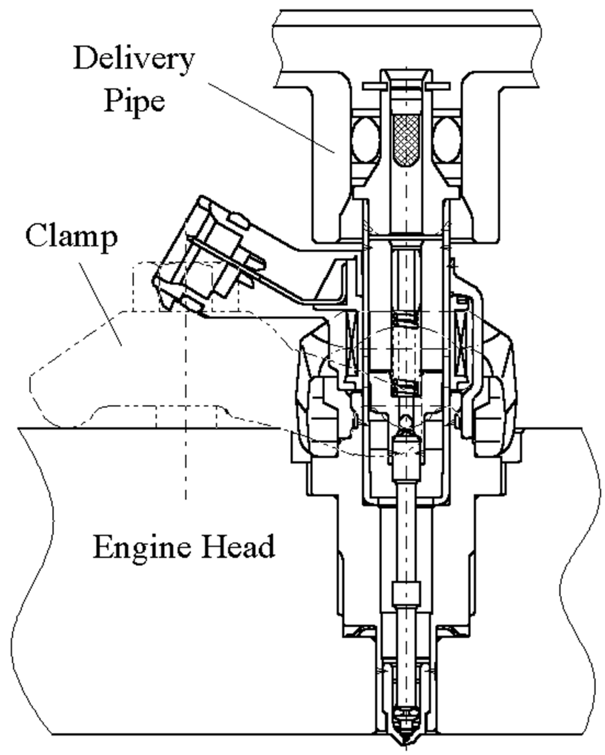

Figure 3. Installation of the Injector

The engine head fasteners and the engine cylinder gas seal are important features for the installation of the injector in the engine. In the production injector, the engine head fastener and the yoke are constructed of a single part, and the cylinder gas seal is constructed as a separate part. However, with the newly developed injector, the engine attachment part is entirely separate and the head fastener and cylinder gas seal are constructed of a single member. Therefore, it is possible to modify the installation configuration in the engine by replacing only this member.

As a result of these features, all parts of the injector fit in a construction such that assembly is able to be performed from one direction, as shown in figure 4, thereby facilitating assembly line automation.

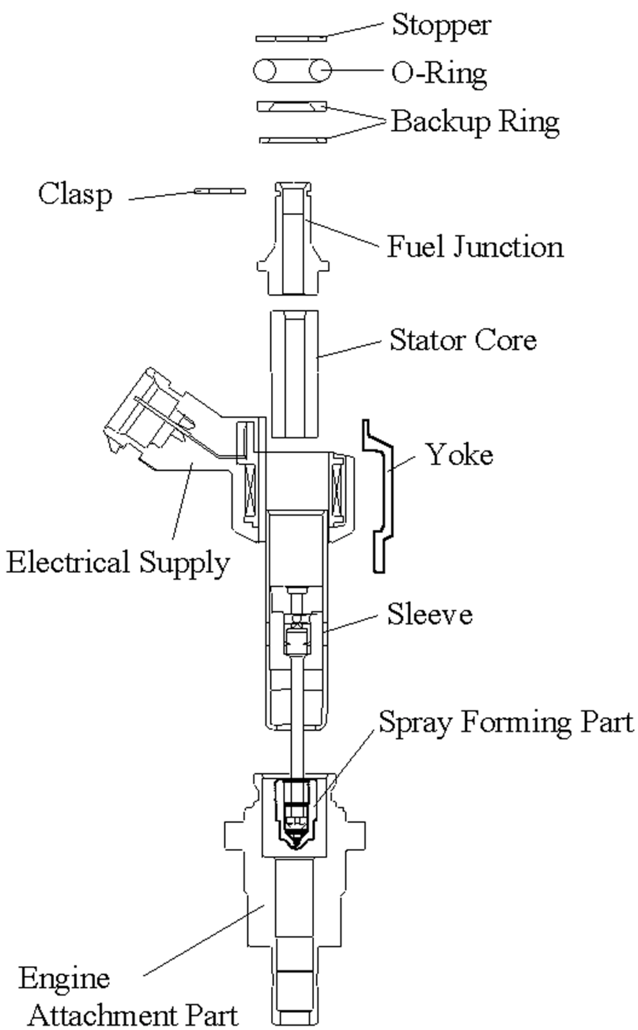

Figure 4. Assembly Process

DESIGN OF ACTUATOR

APPLICATION OF A COMPOSITE MAGNETIC MATERIAL – Figure 5 shows the construction of the electromagnetic valve and the magnetic circuit. The electromagnetic valve is composed of a stator core, a moving core, a yoke, a coil, and a sleeve. In order to seal the fuel path, a sleeve is used. It is desirable that the sleeve is constructed from a ferromagnetic section and a paramagnetic section to maximize magnetic flux transfer from the moving core to the stator core. Therefore, current injectors for port-injected engines are constructed by joining ferromagnetic and paramagnetic sections by welding as shown in figure 6. However, this method is costly and presents difficulties in term of sealing, so it was desirable to use a composite magnetic material as a material of the sleeve. The composite magnetic material has both ferromagnetic and paramagnetic sections in one continuous piece.

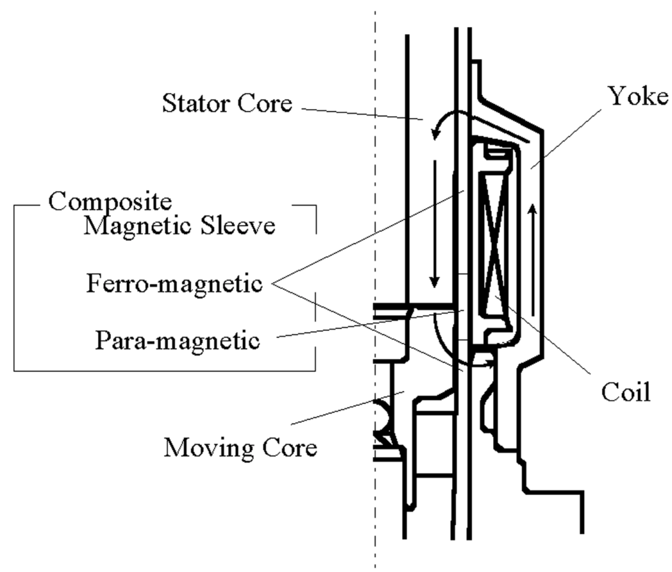

Figure 5. Magnetic Circuit

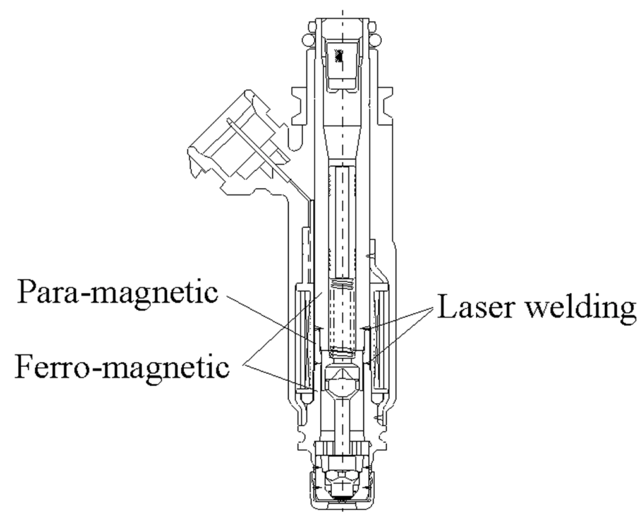

Figure 6. Injector for Port-Injected Engine

The base material of the composite magnetic material is an austenitic stainless steel which exhibits a paramagnetic property.

It is well known that austenitic stainless steels are composed of austenite after solid solution treatment, and that these materials exhibit paramagnetic properties. Furthermore, the austenite phase may be transformed to martensite through cold working, so called deformation-induced martensite, and the resultant martensite phase is ferromagnetic. Therefore, when a part of this martensite is transformed to austenite by heat treatment, a composite magnetic material is obtained.

Unfortunately, the amount of deformation-induced martensite formed upon cold working is small in typical austenitic stainless steels, such as AISI type 304[2], and these steels have insufficient ferromagnetic properties, low magnetic flux density, and low maximum permeability. Magnetic flux density, B40 (induction at H=4000 A/m), for test samples after 70% cold reduction and relative permeability after solid solution treatment are shown in figure 7 as a function of nickel content Heq[3]. Heq is Hirayama's Ni equivalent [4] and defined as follows:

Heq =[Ni]+0.65[Cr]+0.98[Mo]+1.05[Mn]+0.35[Si]+12.6[C]

where [Ni], [Cr], etc. are elemental concentrations in wt% of constituents in the steel of interest. As seen in figure 7, a chemical composition which optimizes magnetic properties may be arrived at. Magnetic flux density indicates that (Ni) should be held below 21.5 wt%. Relative permeability should be at a minimum and the data in figure 8 indicates that optimum performance is obtained with Heq above 20.5 wt%.

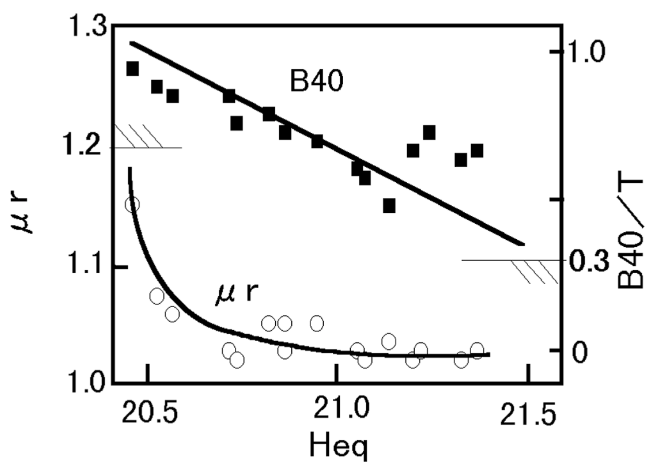

Figure 7. Variation of Magnetic Properties as a Function of Hirayama's Ni equivalent: Heq

A production process for the manufacture of the composite magnetic sleeve is illustrated in figure 8.

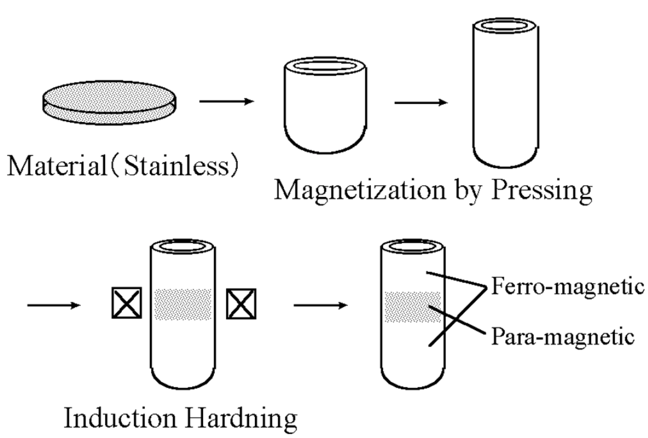

Figure 8. Composite Magnetic Material

Next, the magnetic force obtained when using a sleeve with minimum magnetic flux density was verified. For other parts (stator core, moving core, and yoke) which compose the magnetic circuit, 13 Cr electromagnetic stainless steel is used, just as in mass production. On the assumption that the magnetic flux density of the sleeve is 0.3T at B40, a comparison of magnetic force by analysis of the dynamic magnetic fields of a mass produced injector and of the newly developed injector is shown in figure 9. As an analytic condition, the driving circuit has a condenser whose capacity is 10xe^{-6} F and the voltage is 150v. Compared to the mass produced injector, the newly developed injector shows an 18% increase at maximum magnetic force, and the maximum controllable fuel pressure is increased from 13MPa to 15MPa.

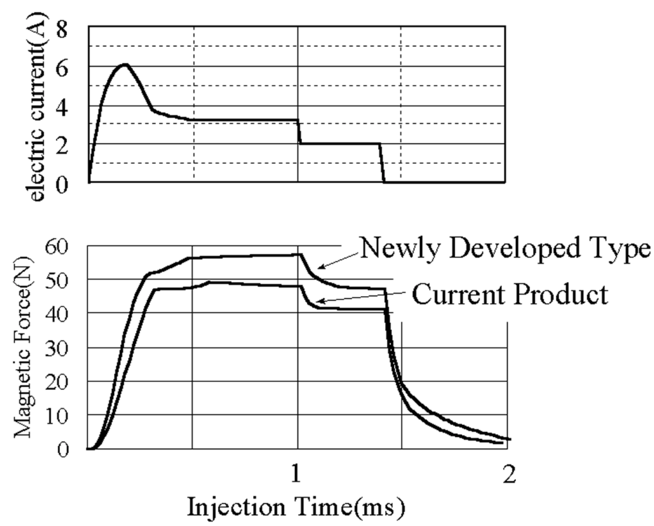

Figure 9. Magnetic Force

CHARACTERISTICS OF THE NEWLY DEVELOPED INJECTOR

FUEL SPRAY CHARACTERISTICS – Spray is a key characteristic that determines engine performance. The required characteristics depend on combustion concepts envisioned by each engine manufacturer. Therefore the spray forming part is constructed as a separate body so that the requirements of different engine installations can be met by replacing only the spray forming part.

First, we explain the forming of the swirl spray.

Figure 10 shows the construction of the swirl injector which consists of the engine attachment part, the spray forming part, the swirler, and the needle. The result of an actual spray observing is shown in figure 11. The results were observed with stroboscopic pictures at 2ms after the start of injection. Generally, the direction of the axis of injectionis determined by the angle of installation of the injector on the engine head and by the shape of the piston.

Next, we explain the forming of the fan spray which is adopted in the TOYOTA D-4 system.

Figure 12 shows the slit nozzle. This slit is very thin like a fan form, and the axis of injection direction is determined by the angle of installation of the injector on the engine head, like with the swirl injector. This slit is processed by fine electric discharge processing as shown in figure 13.

We analyzed how the fan spray is formed using this slit nozzle as shown in figure 14. Fuel flows into the sac from the valve seat, and it can be observed that it spreads out fan-shaped in the slit.

The result of an actual spray observing is shown in figure 15. It was observed with stroboscopic pictures at 2ms after the start of injection into the atmosphere. As a result, it is found that fan spray is homogeneous and thin.

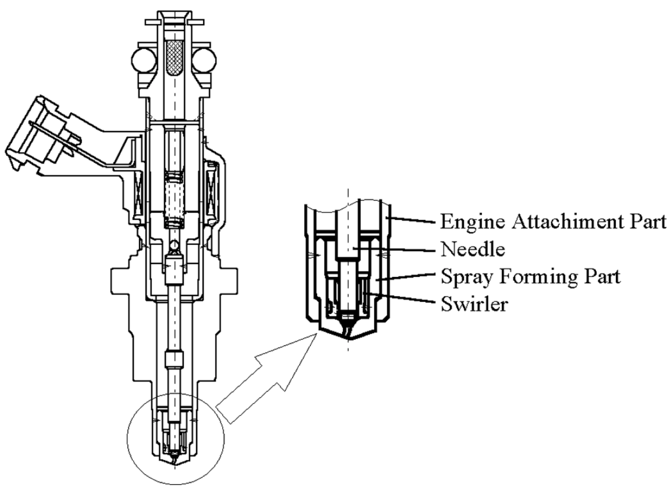

Figure 10. Construction of Swirl Injector

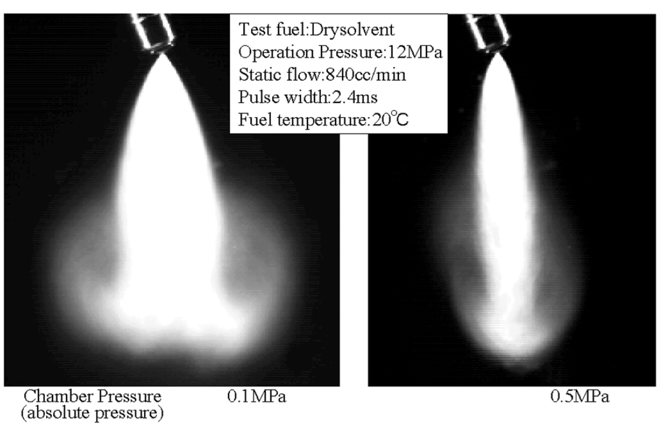

Figure 11. Swirl Spray

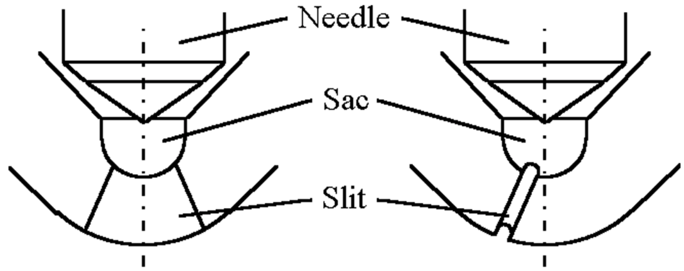

Figure 12. Slit Nozzle

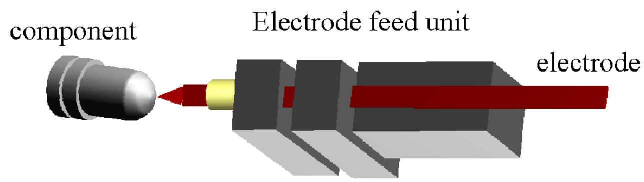

Figure 13. Fine Electric Discharge Processing

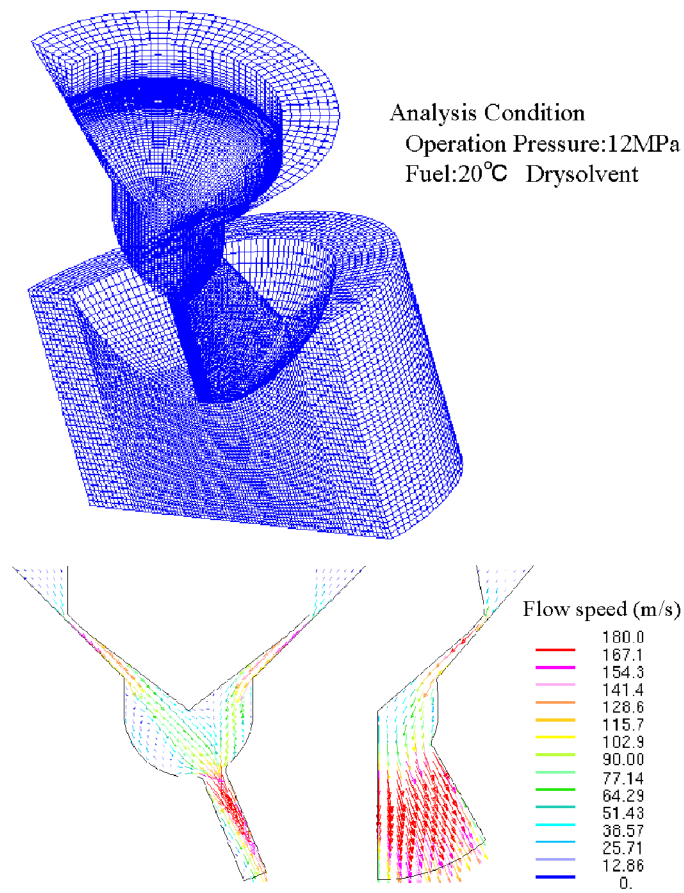

Figure 14. Flow Analysis

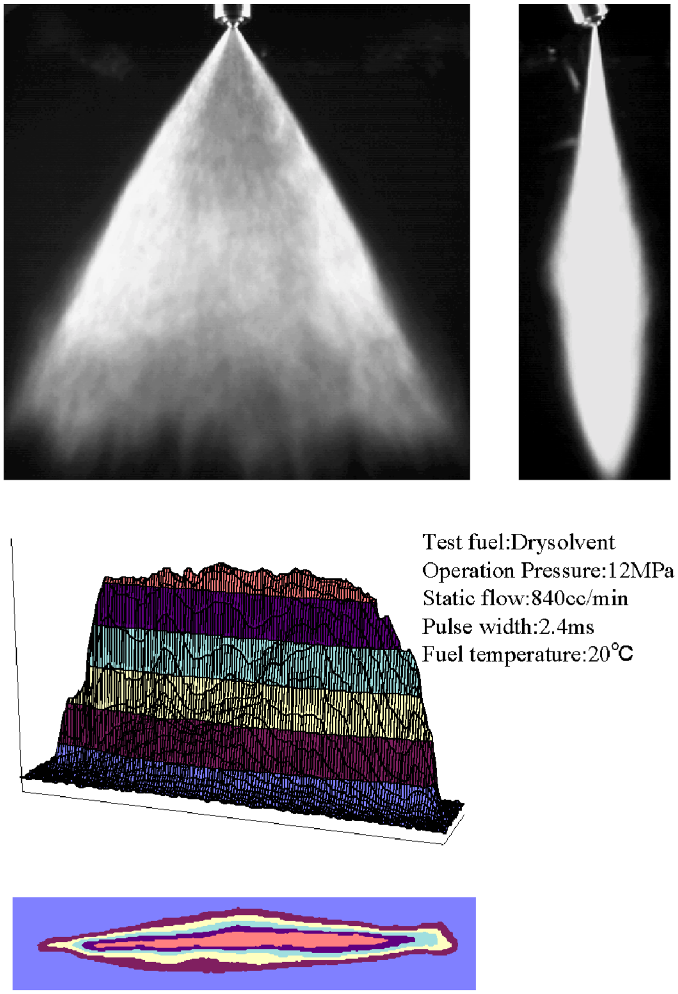

Figure 15. Spray Patterns and Spatial Distributions

CONCLUSION

This paper has proposed the following as a newly developed injector.

1. An 18% improvement in magnetic force characteristics and thus an improvement in injection characteristics relative to a mass produced injector by using a composite magnetic material for the magnetic circuit and the fuel seal of the injector actuator.
2. A structure in which the engine attachment part and spray forming part are constructed as separate parts so as to enable compatibility with the installation and spray requirements of the engine.
3. Modularization of the coil and electrical supply, and thus simplification of the seal structure.
4. The ability for all assembly to be performed from one direction, thereby facilitating assembly line automation according to the aforementioned numerals 1 through 3.

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