

# In-cylinder Optical Investigation of Combustion Behavior on a Fast Injection Rate Diesel Common Rail Injector

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## ABSTRACT

The field of diesel combustion research is producing numerous reports on studies of premixed combustion, which promises simultaneous reduction of both NO<sub>x</sub> and soot, in order to meet increasingly stringent regulations on harmful emissions from automobiles. However, although premixed combustion can simultaneously reduce both NO<sub>x</sub> and soot, certain issues have been pointed out, including the fact that it emits greater quantities of unburned HC and CO gases and the fact that it limits the operating range. Furthermore, this combustion method sets the ignition delay longer with the aim of promoting the mixing of fuel and air. This raises issues with the product due to the combustion instability and sensitivity to the uneven fuel properties that are found on the market, the capability of the engine response under transient conditions, the deterioration in combustion noise, and so on.

Here, therefore, the authors have sought to reduce harmful emissions from conventional diesel diffusion combustion without relying on mixing enhancement that uses ignition delay. This was accomplished with a prototype injector that achieves a faster injection rate of approximately 80% or more than a mass production model piezo-driven common rail injector that complies with EURO 5 standards by enhancing the injection rate from the opening of the nozzle needle up to full lift (hereafter referred to as fast injection rate) while keeping the nozzle hole diameter small. The prototype injector achieved this by making the fuel-air mixture leaner without increasing the fuel pressure, or in other words without an adverse effect on fuel consumption due to increased work by the fuel pump, and thus yielded a reduction in harmful emissions. This was confirmed by evaluation of the spray characteristics and by experiments using a single-cylinder engine, the results of which were reported.

The further investigation here reproduced the combustion of a metal engine in an optical engine and used a high-speed video camera to capture time series flame images. These were used to conduct

detailed analysis of flame behavior in the combustion chamber in time series. The results confirmed that enhancement of the penetrating capability of the spray due to the faster injection rate increased the spread of flame in the central portion of the combustion chamber and enhanced air utilization. The two-color method was also used to analyze the spatial distribution of the flame temperature and the KL factor, and its behaviors over time. This showed that the faster injection rate resulted in curbing combustion in the rear portion of the fuel spray, which is the portion where air is introduced to the spray, so that maximum temperature of the flame is reduced. It also showed that soot was oxidized sooner.

## INTRODUCTION

In response to the global warming of recent years, governments have been considering more stringent controls on CO<sub>2</sub> in addition to the controls on harmful exhaust gases from automobiles. Diesel engines have greater thermal efficiency than gasoline engines, making them more advantageous in terms of reducing CO<sub>2</sub>. They have also achieved cleaner emissions with recent advances in technology centered on turbo charging and fuel injection that have been made in order to comply with stringent emission standard. In these reasons, diesel engines have consequently had an expanding share of the market especially in Europe. One of the key technologies for achieving cleaner emissions is common rail fuel injection technology[1]. Measures being taken to comply with regulations on harmful emissions have begun centering largely on injectors that use actuators with piezo elements in order to heighten the accuracy and response of fuel injection. For aiming to reduce harmful emissions further, research on ultra-high injection pressure, high-precision fuel injection technology which presupposes multiple injection of fuel and other such researches are also underway [2-5]. In the field of combustion research, there have been numerous reports on studies of premixed combustion, which enables simultaneous reduction of

NO<sub>x</sub> and soot[6-11]. Although simultaneous reduction of NO<sub>x</sub> and soot is possible with premixed combustion, other issues have been identified such as greater emissions of unburned HC and CO gases and limitations on the operating range. Furthermore, this combustion method sets a long ignition delay with the aim of enhancing the mix of fuel and air, which also raises product issues with combustion instability and sensitivity to the uneven fuel properties that are found on the market, the capability of the engine response under transient conditions, the deterioration in combustion noise, and so on.

The authors therefore decided to aim for reduction of harmful emissions by conventional diesel diffusion combustion without relying on mixing enhancement that utilizes ignition delay. This was accomplished with a prototype injector that achieves a faster injection rate of approximately 80% or more than a mass production model piezo-driven common rail injector that complies with EURO 5 standards by enhancing the injection rate from the opening of the needle valve up to full lift (hereafter referred to as faster injection rate) while keeping the nozzle hole diameter small. The prototype injector achieved this by making the fuel-air mixture leaner without increasing the fuel pressure, or in other words without an adverse effect on fuel consumption due to increased work by the fuel pump, and thus yielded a reduction in harmful emissions. This was confirmed by evaluation of the spray characteristics and by experiments using a single-cylinder engine, the results of which were reported [12,13].

The research here reproduced the combustion of a metal engine in an optical engine and used a high-speed video camera to capture images from the bottom of the combustion chamber. These were used to conduct observation of flame behavior in the combustion chamber, and analysis of the flame temperature and soot concentration by the two-color method showed in detail how the faster injection rate had the effect of reducing harmful emissions.

## THE COMMON RAIL INJECTORS

This section will describe the main characteristics of the prototype injector used in this study. Further details may be found in previous reports[12,13].

### INJECTOR STRUCTURE AND CHARACTERISTICS OF NOZZLE FLOW RATE

Table 1 shows the specifications of the injectors used in this study and Figure 1 shows a cross-section of the prototype injector structure. The mass production type common rail injector uses a piezo element to control the background pressure activating a nozzle needle. On the other hand, the prototype injector uses a piezo element to control the common rail hydraulic pressure by means of a valve, and this controlled high pressure fuel in the common rail directly actuates the opening and closing of the nozzle needle to obtain fast injection rate performance. In order to further enhance the injection rate during the initial phase of injection,

the seating angle of the nozzle needle was broadened significantly relative to the mass production type injector, as shown in Figure 2, for the purpose of enlarging the aperture area when the needle is at low lift. Figure 3 shows the test results of flow rate characteristics when the nozzle with the specifications shown in Table 2 is attached. It can be confirmed from the figure that using a broader seating angle achieves the aim of producing a significantly increased fuel flow when the needle is at low lift.

**Table 1.** Specifications of common rail injection system

| Injector             | Mass product          | Prototype                    |
|----------------------|-----------------------|------------------------------|
| Max.Pressure (MPa)   | 200                   | 200                          |
| Max.Injection events | 5                     | 5                            |
| Actuator             | Piezo                 | Piezo                        |
| Needle actuation     | Back pressure control | Fuel pressure direct control |

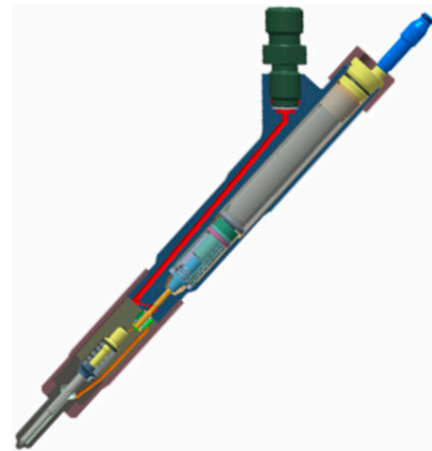


**Figure 1.** Cross section of the prototype injector

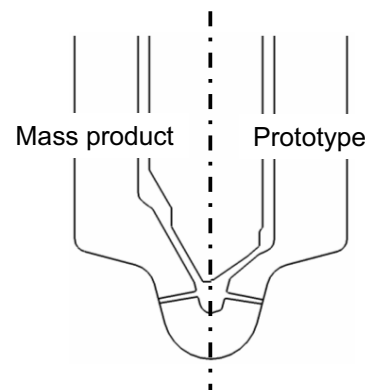


**Figure 2.** Cross section of the injector nozzles

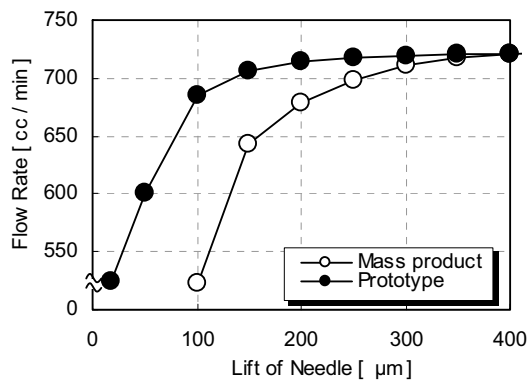


**Figure 3.** Comparison of nozzle flow rate

**Table 2.** Specifications of injector nozzles

|                               | Mass product | Prototype |
|-------------------------------|--------------|-----------|
| Hole diameter (mm)            | 0.12         | 0.12      |
| Hole number                   | 8            | 8         |
| Spray cone angle (deg)        | 160          | 160       |
| Flow rate (cc/min)            | 740          | 740       |
| Sac volume (mm <sup>3</sup> ) | 0.17         | 0.40      |

#### CHARACTERISTICS OF INJECTION RATE

The injection rate measurement device with a system configuration as shown in Figure 4 was used to evaluate the injection rate, which constitutes the basic injector performance. A pressure vessel filled with fuel under 2.0 MPa of pressure had fuel injected into it. Waveform processing of the pressure changes that occur inside the vessel during injection yields the injection rate[14]. Figure 5 shows the results of measurement when injection occurs with a fuel injection amount of 18 mm<sup>3</sup>/st and an injection pressure of 100 MPa, which were the injection conditions during the experiments of spray characteristics and of engine combustion, to be described below. The slope of the injection rate of the prototype in the initial injection phase was 78% larger than that of the mass production type. It confirms that the system employed here yielded a significant enhancement in the injection rate during start-up.

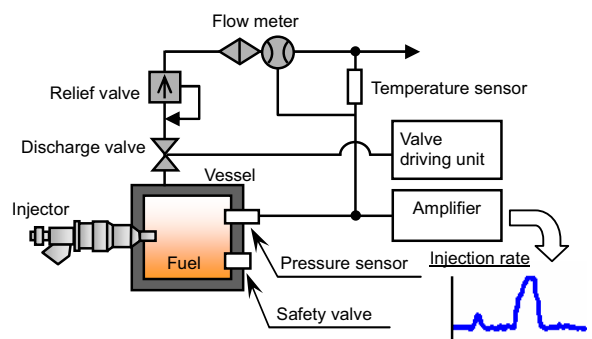


**Figure 4.** Schematic diagram of injection rate measurement

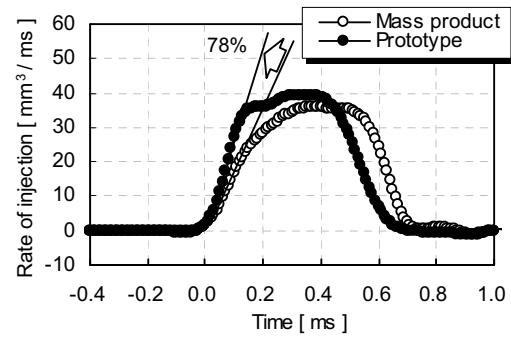


**Figure 5.** Comparison of fuel injection rate profiles (1/4 Engine Load condition)

In addition, the two types of injector showed generally the same trailing edge performance for rate of injection when injection ends.

#### CHARACTERISTICS OF SPRAY

A constant volume vessel and high-speed video camera (Photron FASTCAM-APX RS) was used for spray observation in order to investigate the effects of injection rate enhancement on spray characteristics. Figure 6 shows an overview of the measurement and Table 3 shows conditions of experiment. Image capture took place with a manual focus lens (Nikkor F f/1.2) with a fixed focal length of 50 mm, a recording speed of 10,000 fps, resolution of 512 × 512 pixels, and an exposure time of 2 μs. The experiment was conducted with the vessel charged with N<sub>2</sub> gas at 1.4 MPa to provide the same ambient density at the timing as for fuel injection during the engine experiment. Table 4 shows the specifications of the fuel used for measurement. Fuel was injected into the vessel with a fuel injection amount of 18 mm<sup>3</sup>/st and an injection pressure of 100 MPa. These were the same conditions used in the engine experiment, which will be described later. A high-speed video camera was used to capture images, from which spray penetration and spray angle were determined. The spray volume was also calculated on the assumption of rotational symmetry of the spray with respect to the central axis. Figure 7 shows that the differing injection rate characteristics of the two injectors result in widely diverging spray characteristics, and enhancement can be confirmed such that, at 0.5 ms after start of injection, the prototype injector has 23% greater penetration than the mass production type and 28% greater spray volume.

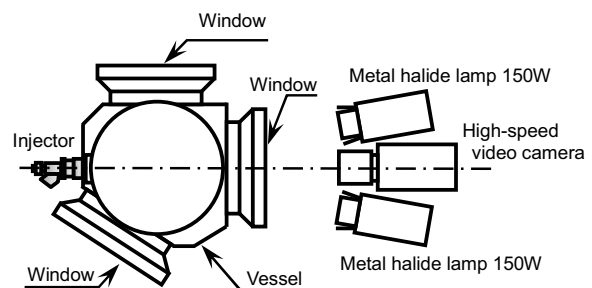


**Figure 6.** Schematic diagram of spray measurement