Study of High Speed Diesel Engine Combustion Using High Speed Photography – Attempt to Obtain All Aspects of Combustion and Its Improvement

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ABSTRACT

Improvement of the high-speed photography technique for diesel engine combustion test and application of the test results to the engine development are described. To investigate the spray (flame) distribution in the piston cavity and the piston top clearance, the authors developed a transparent plastic piston crown, instead of a conventional glass piston crown in the photography system for viewing combustion from underneath, with high durability, wider view of combustion chamber, allowing higher engine speed, and more adaptability to shape of the piston cavity. The test results indicate that it is very important for the improvement of engine combustion to control fuel distribution to match dynamic air distribution in the combustion chamber. The test results obtained were applied to combustion tuning of a single cylinder engine and were also applied to development of an actual engine that cleared exhaust emission regulations in Japan.

INTRODUCTION

Basic research into diesel engine performance development is being undertaken systematically in the areas of inlet and exhaust, injection and combustion systems. In combustion system research, high-speed photography has been proved as a valuable tool to obtain deeper insights into the phenomena of the combustion process. Generally, such investigations have been carried out in three ways: (a) viewing combustion from the top through a transparent window in a cylinder head (1, 2), (b) through endoscopes in a cylinder head (3), and (c) from underneath through an elongated piston with transparent piston crown (4, 5).

So in our experiment, the third system was adopted to obtain all aspects of the combustion area, with a plastic transparent piston crown instead of a conventional glass piston window. Furthermore, schlieren photography was used to investigate the beginning of fuel injection and combustion process, and also an oil points method was used for airflow pattern visualization in the combustion chamber.

This report describes these apparatus and results, and the example of application to combustion tuning of a single-cylinder engine and to combustion improvement of a multi-cylinder engine.

TEST APPARATUS

Fig.1 shows a schematic diagram of the apparatus for direct photography. In this experiment, a reconstructed single-cylinder engine as specified in Table 1 was used. Combustion is viewed from underneath through an elongated piston with a transparent plastic piston crown. A xenon 2 kW lamp was used for lighting the combustion chamber, and a halogen 1 kW lamp for lighting the engine crank maker. The high-speed camera used was Hitachi 15HD manufactured by Hitachi Ltd. Maximum photographic speed was 8000 f.p.s./16000 f.p.s. (in half size).

In the conventional photography system viewing from underneath, the quartz or heatresisting glass has been used as a transparent piston window. Therefore, engine speed has been limited as high as 1000 rpm mainly because of thermal stress and cylinder pressure, and it is hard to obtain the same shape of a piston cavity as in an actual engine.

So, the authors tried to use the transparent plastic material instead of glass and got the following improvement: (1) Transparent plastic piston crown is strongly resistant to cracking caused by heat shock. As a result, our tests could be carried out up to an engine speed higher than 80% of the rated speed, and even in a super-charged condition. This was also confirmed in the case of a higher speed engine. (2) The piston crown was fixed to the elongated piston by slim bolts. So, all aspects of combustion in the chamber could be observed. (3) Since plastic is easy to work, the combustion in the special shaped cavity could also be observed.
attached under the cylinder head. Piston B was used in Fig.2. The 2 kW xenon lamp and the other parts of the apparatus in Fig.1 were used effectively for this photography system.

Furthermore, to investigate the air flow patterns in the combustion chamber, oil points method was used. Tests were carried out by the engine shown in table 1.

![Fig.3 Schematic diagram of apparatus for schlieren photography for engine combustion](image)

**TEST PROCEDURE**

Test procedure for direct photography was as follows. At first, the test apparatus was warmed up to the specified test conditions. Next, the test engine was motored to the specified engine speed, then the high-speed camera and the injection pump were operated by a synchronizer. To obtain the same combustion characteristics both on the test engine and on an actual engine, intake air temperature and pressure were controlled. Injection conditions were all the same as an actual engine. Cetane improver was added to the injected fuel to obtain the same ignition delay as an actual engine. The number of combustions in a test cycle were limited to 5 - 10 times, because of piston contamination by soot and piston distortion by heat.

Cylinder pressure, injection pressure, etc. were recorded by a data recorder being analyzed after testing.

Schlieren photography was taken in the same procedure as the direct photography.

To investigate flow patterns in the combustion chamber the oil points method was used. The authors used colored silicone oil on the surface of the piston top and the piston cavity of the actual engine. The engine was motored at the specified speed for a minute. The flow pattern photographs were taken by a still camera after the engine had come to a stop.

**TEST RESULTS**

The following items concerning fuel spray distribution were analyzed from photographs covering a wider combustion area.
Fig. 4 Examples of direct photographs: Piston type is "A" in Fig. 2. See type A in Fig. 27. (Ne=1000 rpm)

Fig. 5 Examples of direct photographs: Piston type is "B" in Fig. 2. (Ne=1500 rpm)

1. Flame diffusion or propagation in the piston cavity.
2. Flame outflow to the piston top clearance.
3. Swirl velocity derived from flame motion.

Observation of combustion in the piston cavity
Figs. 4 and 5 show examples of the direct photograph. Fig. 4 is an example of piston type A in Fig. 2. At 6° ATDC, one part of the flame (spray) appears to go up along the cavity wall and to go out toward the piston top clearance, while the other part of spray appears to go down and to spread out at the bottom of the cavity, being blown off by a swirl. This example shows the case where the distribution of fuel spray in the cavity and in the piston top clearance is relatively good. Fig. 5 shows a similar example of piston type B in Fig. 2. These photographs show that the air in the cavity is not utilized efficiently for combustion. At 40° ATDC, the bottom of the cylinder head is seen among a lot of remaining dark unburned flame that would become the exhaust smoke.

Flame diffusion in the cavity
Fig. 6 shows an example of flame diffusion in the cavity appearing in Fig. 5. During 6°-10° ATDC, flames 3 and 4 spread out wider than flame 1. At 6° ATDC, flames 3 and 4 begin to contact each other at the cavity wall. At 8° ATDC, the portion of the cavity around sprays 3 and 4 is filled with flames. However, around spray 1, air remains unutilized for combustion. After 8° ATDC, part of flames 3 and 4 turn into dark flames and remain till late at combustion process, as mentioned above.

Fig. 6 Flame diffusion in the piston cavity

Figs. 7 and 8 show the effect of engine speeds on the flame diffusion. Injection timing is about 5° BTDC in these cases. In the case of the same injection timing the higher the engine speed, the later the diffusion. However, Fig. 8 shows that the diffusion itself is faster in relation to the engine speed.
dark flame is one of the main reasons for higher exhaust smoke levels at low engine speed range as shown later (in Fig.25).

Effect of swirl ratio on flame diffusion Fig.10 shows the effects of swirl on flame diffusion in the piston cavity and flow in the piston top clearance. In the cavity, the higher the swirl ratio, the faster the flame diffusion as expected. However, in the piston top clearance, in the case of high swirl, flame spreads out slowly first. As combustion pressure becomes higher, the flame spreads out faster than in the case of low swirl.

Flame outflow in the piston top clearance At TDC, the clearance between cylinder head and piston top is about 1.0 mm. The volume of this space is about 10 - 20% of the total volume of the combustion chamber. In this area the flame easily turns into soot because of its lower temperature. This was made clear by Aoyagi, et al.(2). Therefore, the authors paid attention to the flame outflow in the piston top clearance or squish area, which is one of the most important factors for controlling combustion.

Effect of engine speed on flame outflow Fig.9 shows the flame outflow in the top clearance. The lower the engine speed, the wider the flame area, and the darker the flame in photographs. This

Imbalance of flame outflow Fig.11 shows an example of photographs in a case where there is imbalance of outflow among five flames. Fig.12 shows that flames 3 and 4 spread faster and darker than flame 1.
Fig. 12 Imbalance of flame outflow in the piston top clearance; See Fig. 11. (Ne=800 rpm)

Swirl ratio derived from flame motion
The authors obtained swirl ratio from flame motion long after the end of fuel injection.

Effect of engine speeds. Fig. 13 shows the effect of engine speeds on swirl ratio \( \omega_c / \omega_e \). Swirl ratio does not depend on engine speed, and decreases 3-4% per 10 deg. crank angle during the combustion process.

![Diagram showing swirl ratio in the cavity](image)

**Fig. 13 Swirl ratio in the cavity derived from combustion flame; Effect of engine speed**

Effect of piston cavity diameter. Fig. 14 shows the effect of cavity diameter \( d_c \) on swirl ratio \( \omega_c / \omega_e \) in the cavity. The smaller the piston cavity diameter, the higher the swirl ratio.

![Diagram showing influence of chamber diameter on swirl ratio](image)

**Fig. 14 Influence of chamber diameter on swirl ratio in the cavity**

Fig. 15 shows the correlation among swirl velocity \( N_s \) in the piston cavity, swirl ratio \( N_s/N_e \) (3), cavity diameter \( d_c \), and engine speed \( N_e \). Swirl velocity is approximately proportional to swirl ratio \( N_s/N_e \) calculated by the data obtained in steady flow test, engine speed \( N_e \), and \( d_c \). The swirl velocity \( N_s \) derived from flame motion is about half of the velocity derived from steady flow test. This result agrees with velocity decay during the compression process, which was calculated by Kido, et al. (9).

![Diagram showing swirl velocity in the piston cavity](image)

**Fig. 15 Swirl velocity in the piston cavity**

**Observation of airflow and fuel spray delivery imbalance in the cavity**

Fig. 16 shows examples of schlieren photographs and Fig. 17 is a sketch of one of them. Sprays 1 and 4 spread out faster than 2 and 3, and spray 3 is blown off by the strong airflow. Then the authors investigated the airflow in the cavity and the fuel spray delivery.

![Images of schlieren photographs](image)

**Fig. 16 Example of schlieren photographs**

![Sketch of schlieren photograph](image)

**Fig. 17 Sketch of schlieren photograph**

**Imbalance of airflow in the piston cavity** Fig. 18 shows an example of flow visualization by oil points method, and Fig. 19 shows the example of sketches. In the case where the cavity offset to the piston center is small, it shows that there is a stronger airflow at the offset.
side of the cavity, as if a vortex center would be at the piston center. With the increasing cavity offset to the piston center, the air motion seems to have a velocity component that is parallel to the cylinder axis in addition to its own swirl motion.

Fig. 18 Example of flow visualization by oil points method

![Image](image1.png)

Fig. 19 Effect of cavity offset on the airflow patterns by oil points method

![Image](image2.png)

Imbalance of fuel delivery. Fuel delivery through each nozzle orifice would be influenced by flow coefficient; arrangement and shape of orifice entrance and Reynold's number (fuel velocity). In the schlieren photograph as shown in Fig. 16 fuel spray imbalance is evident. The authors measured the fuel delivery through each nozzle orifice. Fig. 20 shows an example of a test result for a nozzle with four orifices. Delivery of sprays 1 and 4 are more than sprays 2 and 3. The fuel quantity deviation of this type of nozzle is in a range of about 15%.

![Image](image3.png)

Fig. 20 Example of fuel quantity deviation by each nozzle orifice

Fig. 21 shows the influence of a nozzle orifice inclination angle to the needle axis on fuel delivery. The smaller the nozzle orifice inclination angle, the more the fuel flows out.

![Image](image4.png)

Fig. 22 Nozzle orifice directions and combustion chamber for tuning test

**Type A**: Direction of each spray is equiangular (72°).
One of the sprays is square to the piston pin.

**Type B**: Direction of each spray is equiangular (72°).
One of the sprays passes through the cavity center.

**Type C**: Impinging point of each spray is equidistance along the cavity wall. One of the sprays passes through the cavity center.

APPLICATION TO ENGINE COMBUSTION IMPROVEMENT -- SINGLE-CYLINDER ENGINE

From the above test results, it was assumed that two kinds of tuning were necessary for combustion improvement. One was fuel distribution tuning in the piston cavity in order to improve imbalance of airflow in the piston cavity and of fuel delivery. The other was fuel spray outflow tuning from the piston cavity to the piston top clearance. Tuning tests were carried out using a single-cylinder engine.

Fig. 22 is a schematic diagram of nozzle orifice directions of a test nozzle. These were designed to improve the imbalance of fuel distribution in the piston cavity around the sprays 3 and 4 shown in Fig. 6. The test case of nozzle type A and piston cavity diameter $dc=75$ mm corresponds to Figs. 5 and 6.
Fig. 23 shows the test results of the effects of nozzle orifice directions and piston cavity diameters. In the case of the largest cavity diameter (dc=75 mm), nozzle type A did not provide sufficient good combustion as type C in terms of exhaust smoke and brake mean effective pressure (b.m.e.p.), because it had the imbalance of flame distribution in the piston cavity as shown in Figs. 5 and 6. In the case of a smaller cavity diameter (dc=73 mm), nozzle type A was the best in respect of exhaust smoke and b.m.e.p. among three nozzle types. However, in the case of the smallest diameter (dc=70 mm), nozzle type C was the best among these three.

From these results it became clear that there would be suitable spray directions for good combustion in relation to the cavity diameter.

Photographs shown in Fig. 24 were taken on this condition.

Fig. 24 Photographs of nozzle orifice directions tuning shown in Fig. 23 (Ne=1000rpm, 40° ATDC)

Fig. 25 Sectional views of piston cavities for the study of effects of cavity wall inclination.
Fig. 26 shows the test results of the effects of piston cavity wall inclination. In the case the cavity wall inclination angles were 10° and 20°, the deterioration of exhaust smoke and b.m.e.p. were slight, at the late fuel injection timing to reduce NOx formation.

The effect of cavity wall inclination on the flame outflow to the piston top clearance was also observed in another test.

APPLICATION TO MULTI-CYLINDER ENGINE DEVELOPMENT

The test results of the above combustion observation and tuning tests by a single-cylinder engine were applied to the multi-cylinder engine development.

Fig. 27 shows an example of the results of the effects of piston cavity wall inclination and nozzle spray cone angle. Type A is a nozzle-cavity combination that controlled the swirl velocity by cavity diameter, fuel distribution in the cavity by nozzle orifice direction, and flame outflow by cavity wall inclination and spray cone angle tuning. Type B is the combination of a conventional piston cavity and a nozzle. Type A was better by about 2 Bosch unit in exhaust smoke and about 3% in torque than type B. These two types had the same fuel delivery characteristic and the same level of NOx under the 6-mode Japanese exhaust emission test cycles for diesel engines.

Fig. 28 shows the effect of nozzle orifice inclination angle on exhaust smoke with respect to type A combination in Fig. 27. Type D is the case of Figs. 11 and 12. There was imbalance of outflow among five flames, as mentioned regarding Figs. 11 and 12. Based on the test results in these figures type C was prepared for better performance. Type C was better than type D by about 0.5 Bosch unit in exhaust smoke at low engine speed.

From the above-mentioned test results it can be said that exhaust smoke is improved by fuel outflow tuning of each nozzle orifice.

SUMMARY

The conclusions of this study are as follows:

1. Use of the newly developed transparent piston crown is very useful for diesel combustion study as it has a wider view, allows higher engine speed, and is adaptable to any shape of cavity. It enables us to understand all aspects of combustion.

2. It is possible to obtain more precise information of fuel injection and airflow by using schlieren photography and oil points method.

3. From the test results of the direct and schlieren photography and the oil points method, tuning tests were carried out using a single-cylinder engine. It was made clear that there
was imbalance of airflow and fuel
distribution in the cavity and in the
piston top clearance. For D.I. diesel
combustion improvement, it is important
to control fuel distribution to meet
dynamic air distribution.

(4) These results were applied to the
development of an actual engine, which
was greatly improved and cleared
Japanese exhaust emission regulation.

(5) These techniques will be helpful for
the confirmation of diesel combustion
modeling and simulation.

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