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A Study on Combustion in Direct-Injection Diesel Engine (3rd Report)*

(Crosssectional Observation of a Shallow-Dish Chamber)

By Makoto IKEGAMI**, Fujio NAGAO***,
Takuji FUJIKAWA⁺, and Takuichi FUJITA⁺⁺

As a sequel to the high-speed photographic studies on combustion in direct-injection diesel engines, the progress of combustion in a quiescent shallow-dish chamber with a multi-hole nozzle centrally located has been investigated by taking a crosssectional view of the combustion chamber. This has been attained with a two-cycle engine with specially designed cylinder-head and piston, which simulates only a sector of the injector and piston-cavity arrangement. As the result of observation, it has been revealed that a considerable amount of the fuel is conveyed to the cylinder head after the spray hits the wall of piston cavity, governing the flame development in the middle and later stages of burning, and that the fuel which penetrates into the clearance space makes a substantial source of soot cloud. Further, the influences of the direction of the fuel spray, the opening pressure, and the profile of the chamber on the progress of burning have been evaluated.

1. Introduction

It is widely accepted that both fuel injection and gas motions govern the mixture formation and the subsequent progress of burning in direct-injection type diesel engines. In the previous papers, the present authors investigated these matters in some detail with various types of combustion chambers by high-speed photography. The first report⁽¹⁾ dealt with the effect of direction of fuel injection and the number of injection nozzles in a quiescent shallow-dish chamber, together with the effect of swirl and the cause of overswirling. The second report⁽²⁾ discussed the effects of chamber form and the gas motion, surveyed in some deep-bowl (or troidal) chambers often employed in compact high-speed engines.

However, all of these high-speed photographic observations were performed from the upward position of the engine through a glass window mounted on the cylinder head, so that the flame developments inside the combustion space could not be fully investigated in three-dimensional aspects, which might play quite an important role in the progress of burning. The same can be said about the similar studies carried out by Alcock and others⁽³⁾⁽⁴⁾.

In order to make a closer survey of this subject, a special cylinder head was newly devised permitting a crosssectional

view of the flame development. The observation under this arrangement was limited to simulating only quiescent chambers having a dished top on piston, nevertheless this well confirmed the findings attained in the first report, yielding simultaneously several additional suggestions for medium or large size engines.

2. Experimental apparatus and procedure

The experiments were carried out with a loop-scavenged two-cycle engine of cylinder diameter 110 mm and stroke 120 mm, the same one used in the previous reports. The cylinder head and piston crown of this engine were so reconstructed as to simulate only a sector of the injector and piston-cavity of a shallow-dish chamber with a multi-hole nozzle centrally located. As is shown in Fig. 1, a projection with a special depression having the same crosssection as the actual engine is installed on the piston crown and is allowed to move in and out in the hollow of the devised cylinder head. On both sides of the cylinder head are installed windows made of a strengthened glass, rendering visible crosswise the progress of burning inside the space between the head and the top of the projection. It may be assumed that this equipment reproduces the flame development from one of the sprays in a hypothetical engine having a cylinder diameter 180 mm. The expected deterioration in scavenging with use of this arrangement could be compensated by adopting double scavenging for each fuel injection, keeping the air purity sufficient for each burning cycle. Injection nozzle employed was of Bosch DLL type with a single orifice of 0.3 mm diameter drilled in a prescribed direction. Injection pump used was of Bosch type PE2B100 having a plunger diameter 10 mm, and the fuel was a diesel fuel

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** Assistant Professor, Faculty of Engineering, Kyoto University, Sakyo-Ku, Kyoto.

*** Emeritus Professor of Kyoto University.

+ Engineer, Mitsubishi Heavy Industries.

++ Engineer, Hitachi Shipbuilding Co.

of specific weight 0.827 and cetane number 70.

The shapes of piston top to be examined are shown in Fig. 2, together with the illustration of each geometrical spray path for the quiescent position of the piston placed at top dead center. Conforming to the common use, the direction of fuel injection is indicated by the total included angle between the hypothetical sprays, which will be called the spray angle hereafter for convenience.

A brief description of the chamber profile is given as follows: Type A is characterized by a sharp-edged rim, type B by a round edge, and type C by a flat bottomed shape with a round edge. For every case, the effective compression ratio was selected to be 12.0, where the swept volume was taken as the cylinder volume at the instant when the exhaust port was just closed by the top ring of the piston. The volume of the test section to be photographed was 53 % of the total compression volume. Indeed this comparatively large value is likely to cause unusual gas motions of some kinds at the end of compression, such as squish or eddies, but these must be put out of the question since they are inevitable in the present experimental set-up.

The state of burning was recorded by a Shimadzu KS-16 type rotating-prism camera, in quite similar manner to the previous studies. In order to prevent the quality of the obtained pictures from deteriorating due to carbonaceous deposits on the glass windows, the motion picture was taken at fifth or sixth firing run after sufficient warming up by motoring. The scavenge air was adjusted to be 80°C at the inlet by using a preheater, with the delivery air ratio regulated to be 1.9. At the instant

Fig. 2 Profile of combustion chamber and direction of spray

The volume of test section is 53 % of total compression space, and crosssectional area of canal between test section and piston is approximately 3.2 % of piston area.

Fig. 1 Cylinder head and piston arrangement for crosssectional observation

of photographing the state of combustion, the engine speed and the fuel quantity were adjusted carefully to be 700 rpm and 37.2 milligrams per firing stroke (estimated excess-air factor 1.6) respectively, although they scattered considerably owing to the transient running condition. The optical system used in this experiment is schematically illustrated in Fig. 3. In order to make visible the contour of the combustion chamber and the spray envelope, a high-pressure mercury lamp of 500 watts was placed on the opposite side to the glass window, together with a suitable moderator for the intensity of illumination. The crank-angle graduation on the flywheel was introduced in the sweep of the camera, in order to gauge the timing of each frame of picture.

3. General observation of mixture formation and combustion

3.1 Injection rate and pressure change

Photo 1 in Fig. 4 presents the high-speed photographs taken at 150° spray angle with type A chamber. The corresponding indicator diagram recorded by a strain-gage type transducer (Kyowa-Dengyo's PHF-10B type) is reproduced in Fig. 5, together with the measured rate of fuel injection indicated in the form of the input of mean effective pressure. The latter was determined by means of Bosch's method⁽⁵⁾ using a delay line of an inner diameter 5 mm and a length 5 000 mm. According to the figure, the period

Fig. 3 Schematic diagram of optical system

of injection is known to be 19° in crank angle. This length may not be so different from what can be expected in an existing engine. According to the record of cylinder pressure, the ignition delay seems to be somewhat longer than usual. This may be attributed to the colder condition due to double scavenging and to the unsteady running. However, the mode of the pressure-time relation does not seem to differ essentially from what occurs in an actual engine, so it may be stated that the progress of combustion taking place may not be so different from the actual one in spite of such an abnormal cylinder head being employed.

3.2 Development of spray and blow up of fuel

From Photo 1, it may be noticed that the actual spray path shows a slight deviation upward from the geometrical one. Never specific to this photo, this was experienced more or less in some other cases. This is attributed neither to the accuracy of drilling nor setting of the nozzle, but rather to the transfer of a "hole in air" produced by spray with the piston displacement. The angle of this deviation amounts to a few degrees in the present case.

In the next place, it can be observed that a considerable part of fuel is blown up at the upper side of the chamber after the spray impinges on the side wall. This implies that the side wall of the chamber may have a large effect on fuel distribution in the chamber space. In Fig. 6 some selected shots taken of types A and C are presented, both indicating the instant of fuel reaching the underside of the cylinder head. For the chamber of type A, the fuel jet is thrown up almost vertically to the head.

3.3 Flaming in the cavity

Turning to Photo 1 in Fig. 4, attention will be now paid to the flame developing inside the piston cavity. Ignition takes place first in the neighborhood where the spray impinges on the side wall, which is then followed by a rapid spread to cover the underside of the spray. At the same time, the flame can develop both in the

Fig. 5 Record of cylinder pressure and rate of injection, at 150° spray angle in A-type chamber (opening pressure 275 kg/cm^2)

2 A-type, 150° ,
 $p_o = 200 \text{ kg/cm}^2$
(740 rpm, 4 500 f/sec)

3 A-type, 150° ,
 $p_o = 350 \text{ kg/cm}^2$
(760 rpm, 4 000 f/sec)

Fig. 4 High-speed photographs (values in parentheses indicate instantaneous engine speed and camera speed)

Upper; 5° b. top dead center, 150° spray angle in A-type (Photo 1)
Bottom; 5° b. top dead center, 150° spray angle in C-type (Photo 9)

Fig. 6 Spray impingement and blow up of fuel

Fig. 7 Motions of flame

upper space and in the clearance, finally spreading over the entire space of the visual field. However, the flame covering the spray envelope is soon overcome by an upper separate flame overhanging from the wall of the cylinder head. In other words, the combustion in middle or later stages is mainly governed by the flame developed from the upper side. A plausible explanation of this phenomenon would be the excessive fuel that has been blown up to the cylinder head, and it may be stated that the air-borne fuel distributed directly on the spray path is less important in such stages.

In the previous study⁽¹⁾, it has been experienced that some gas motions are induced by combustion itself, such as ones indicated as b and c in Fig. 7, and that at less number of sprays an inert lumpish flame may come into sight in the upper combustion space in the middle combustion stages. These matters are quite consistent with the present crosswise observation, namely this lumpish flame corresponds to the flame overhanging from the cylinder head, associated with an anti-clockwise current as represented by Fig. 7b. It is interesting to note that the situation is quite similar between these cases in spite of considerably different conditions in terms of injection and dimension of chamber.

Judging from a large contribution of the spray impingement and the resulting transfer of fuel to the cylinder head, it might happen that the penetration of the fuel spray was not adequate for the combustion system under examination. Referring to the selection of the diameter of the nozzle orifice, it should be mentioned that the adopted diameter of 0.3 mm was a translation from the case of eight holes with 0.18 mm diameter in the previous shallow-dish experiments, calculated on the basis of Wakuri's momentum theory proposing a linearity

150° spray angle,
 $p_{00} = 275 \text{ kg/cm}^2$
(Photo 1)

150° spray angle,
 $p_{00} = 350 \text{ kg/cm}^2$
(Photo 3)

140° spray angle,
 $p_{00} = 275 \text{ kg/cm}^2$
(Photo 5)

Fig. 8 State of soot cloud, at 50° after top dead center, A-type chamber

between diameters of the nozzle orifice and the cylinder⁽⁶⁾. For this end, the cylinder diameters of the original and the hypothetical engine 110 mm and 180 mm respectively were used. According to Wakuri's chart from some survey on the existing engines, the optimum diameter could be read to be 0.27 mm for cylinder diameter 180 mm, suggesting that the adopted one is never inadequate. By consulting another diagram of the allowable spray penetration versus orifice-diameter relation described in Burman and DeLuca's book⁽⁷⁾, the recommended diameter of a spray path 70 mm for natural aspiration turned out to be 0.25 mm under a quiescent condition and 0.43 mm under a condition of turbulent air-flow, again supporting the appropriateness of our selection of the nozzle diameter for a quiescent case. Thus it may be stated that the observed flame developments would reasonably reproduce the actual progress of burning.

3.4 Flame in the clearance and soot formation

In the next place, the outflow of the flame into the clearance space will be discussed. Such an outflow takes place first near the top dead center, associated with a rapid pressure rise occurring during the uncontrolled stage of combustion. Interrupted meanwhile up to 8° after top dead center, the second penetration of flame occurs gradually with the piston displacement. Qualitatively speaking, these phenomena are quite similar to those in the quiescent chamber in the previous report. At crank angles later than 20° after top dead center, the flame in this space begins to fade away, which will finally turn into a heavy soot cloud. Figure 8 reproduces some photographs taken in the last combustion stage, showing that the cloud can be produced from a part remote from the injection nozzle. In such a part, the illumination of background is no longer visible. Considering the fact that the intensity of light recovered once the

charge in the cylinder was renewed by scavenging, the opaque portion there must be a lot of dense soot accumulated during the earlier stages. Such a circumstance to produce a soot cloud could be more adequately observed when the usual monochrome films were substituted by some color films in photography. The result has shown that the flame can burn up earlier in the piston cavity than in the clearance, and that the flame in the clearance lasts longer with a reddish coloration gradually turning darker and darker. These matters are again supported by the previous observation that the flame can burn up earlier in the cavity than in the clearance unless an orderly air motion is present. Such an opaque flaming zone existing in the extreme part will be attributable again to the excessive fuel that has accumulated in the very beginning of burning. Partly because such a fuel can be easily brought into the clearance space assisted by the rapid expansion of gas or the reversed squish, and partly because it may be submitted to quenching by the direct contact with the colder wall, the clearance space must be liable to be in an overrich state accompanied by imperfect burning. In other words, the primary source of soot cloud does not lie in the main combustion space inside the piston cavity but rather in the extreme spaces such as the clearance or the very vicinity of the wall, at least in the case of normal condition different from over-fueling. As will be evidenced in the later examples, this statement seems to be almost true, and it is the authors' belief that the spray penetration should be kept within an allowable degree by using an appropriate means, in order to suppress the soot formation.

3.5 Summary

According to the present observation, the following matters have been revealed.

(1) Under usual spray condition, a considerable fuel may hit the side wall of the cavity, and it is then brought to the wall of the cylinder head. Thus a considerable amount of fuel can accumulate on the upper side of the cavity.

(2) The flame takes place first from the air-borne fuel, covering the entire space of the cavity for a moment. In the subsequent stages after it burns up, the flame is soon substituted by the one produced from the upper side of the chamber, with an appearance of rotary motion.

(3) In the later stages of combustion, the flame remains in the vicinity of the side wall or in the clearance space rather than in the piston cavity, and it finally turns into a soot-forming cloud.

It should be emphasized that the behavior of the fuel after the impingement on the side wall plays an important role throughout combustion. This matter may support Dicksee's view⁽⁸⁾ that the distribution of fuel can be effectively assisted by some splashes from the chamber wall.

4. Influence of various factors

4.1 Opening pressure

In order to evaluate the difference in the flame developments with varying parameters, photographs were taken under several conditions and the results compared. At first, Photo 2 in Fig. 4 shows the record taken under the same condition as Photo 1 except for the opening pressure reduced to 200 kg/cm² from 275 kg/cm². Although it may be stated that the overall course does not differ so much from that of Photo 1, several differences can be noticed between these photos. Presumably owing to the decreased penetration of spray, the flame from the upper side does not develop fully compared to the former case, the access to the nozzle side being hindered in the middle or later stages. Another specific feature of the present case is the creation of a heavy dark soot-cloud which appears as early as 10° after top dead center, and begins to spread from the rim to cover the upper combustion space. In the next place, the opening pressure was raised to 350 kg/cm². As is seen in Photo 3, the flame predominates in the upper side in this case and the flame has more spatial uniformity in luminescence than elsewhere, with less local dark patches. A plausible explanation of this phenomenon may be the improved air-entrainment in spray at higher injection pressures, resulting in less smoky combustion. In fact, the soot cloud could be considerably reduced, as is evidenced in Fig. 8. However, it should be noted that the flame lies a little toward the side of cylinder liner. This might suggest a possibility of poor utilization of the air existing in the nozzle side.

Figure 9 summarizes the results of performance test carried out with a constant fuel quantity for three kinds of chambers, expressed in terms of indicated thermal efficiency versus the opening pressure. It is known from this figure that for each chamber there is a maximum point somewhere between 200 kg/cm² and 350 kg/cm².

Fig. 9 Influence of opening pressure on indicated thermal efficiency (150° spray angle)

4.2 Direction of fuel spray

Photos 4 through 7 in Fig. 10 reproduce the photographs taken at various spray angles with an opening pressure 275 kg/cm^2 in type A chamber. The result of performance test is given in Fig. 11. It is known from this that the indicated thermal efficiency attains a maximum at a spray angle 160° for the type A.

In the case of a smaller spray angle 130° or 140° , Photos 4 and 5, splashing of fuel to the cylinder head is much intensified owing to the reduced angle of incidence relative to the piston cavity. For this reason, the circulating nature in the middle flaming stages (b in Fig. 7) seems to increase in power compared to the case of spray angle 150° . Judging from the fact that in the usual combustion chambers the direction of fuel spray has been so selected as to make a spray angle between 130° and 150° , it may be stated that the blow up of the fuel to the upper parts is automatically utilized to considerable degree in an actual engine. As to the soot cloud in the present case of 140° spray angle, there is no great difference from that of 150° , as can be seen in the bottom of Fig. 8. In this case, the soot cloud looks as if it spouted from the chamber rim.

In the case of a larger spray angle 160° or 170° , respectively corresponding to Photos 6 and 7 in Fig. 10, it was observed that the fuel was distributed directly in the air with less contact with chamber walls. In those cases, the deviation of the spray path from the geometrical one was much pronounced, which would cause an increase in the amount of fuel that

Fig. 10 High-speed photographs (effect of spray angle and chamber form)

Fig. 11 Influence of direction of spray angle on indicated thermal efficiency (opening pressure 275 kg/cm²)

penetrated directly into the clearance space. The deviation amounts to as much as 10° in the case of the spray angle 170°. Owing to this, the circulatory flow associated with the flame is considerably weakened, and the space close to the nozzle is never covered fully with flame in the later combustion stages. Apparently, it was experienced that the production of smoke was considerably heavier.

4.3 Profile of the piston cavity

The quiescent shallow-dish chamber has been designed with various profiles of piston cavity. However, it may be said that the combustion chamber having a round edge is not advantageous with respect to engine performance, because such a chamber will allow easier penetration of fuel into the clearance space. This may be also expected from the state of splashing, as observed in Fig. 6 for type C chamber. This view is actually evidenced by Figs. 9 and 11, showing that the performance of a chamber having a round edge, type B or type C, is always inferior to that of sharp-edged chamber, type A.

Photos 8 and 9 show the records obtained from chambers of types B and C. In the case of B type, it is noticed that the flame does not prevail fully to the nozzle side even as late as 30° after top dead center. Clearly, this is attributable to the weakened circulatory flaming owing to the excessive penetration of fuel into the clearance. In the case of C type, Photo 9, the circulatory flow is still more weakened owing to the decreased depth, preventing the flame from reaching the nozzle side. Thus it may

be stated that the circumference of the combustion chamber has an important connection with the flame development, and that some spatial extent is required for assuring a rapid progress of combustion.

5. Conclusions

By means of a crosssectional observation, the progress of combustion in a quiescent shallow-dish chamber in a direct-injection diesel engine has been investigated. Precisely speaking, it is a little doubtful that the actual progress of burning can be adequately reproduced by the present experiments, but there does not seem to be any doubt about it at least qualitatively. Summarizing the obtained results, the following matters have been revealed.

- (1) A considerable amount of fuel is brought up to the wall of cylinder head after the spray hits the wall of the piston cavity. The flame spreads first from the mixture around the spray, which is soon substituted by the one developing from the upper side of the chamber.
- (2) In the later stages of combustion, the flame remains longer in the clearance space, turning finally into a soot cloud.
- (3) A round edge of the piston rim will permit easier penetration of fuel into the clearance, hindering the development of the flame inside the cavity.

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