# The Combustion Process in Swirl Chamber Type Diesel Engines

By

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High-speed motion pictures taken through glass windows in a full-scale engine, have led to the following knowledge about the combustion process in a swirl chamber type Diesel engine. The gas in the swirl chamber rotates in the same direction throughout the combustion and, after ignition, flows out into the main chamber from its periphery, layer by layer. The fuel-air distribution in the swirl chamber, which depends primarily on the direction of fuel injection, has a predominant influence on the subsequent combustion process. In the case of fuel injection along the air-swirl, the formation of an overrich mixture in the peripheral zone brings about two favorable factors for a rapid and complete combustion; one is the possibility of an earlier outflow of the mixture into the main chamber, and the other is the most effective use of *thermal mixing effect* in the swirl chamber. In addition, these factors were discussed in relation to the performance of a practical engine.

## I. Introduction

The well-known research works of H. R. Ricardo[1] as well as Moore & Collins[2], have already pointed out that the combustion process in a Diesel engine with a swirl combustion chamber depends primarily on the direction of fuel injection into the swirl chamber; but there remains as a problem yet unsolved the actual process of mixture formation and combustion of fuel injected in the chamber. Recently, F. Pischinger and A. Pischinger have published, in their work, new information on the Diesel-combustion in moving air, and further data on the influence of the combustion chamber wall on the combustion in the air-swirl[3].

In the swirl chamber of a practical engine, a further complication is added by the fact that the inflow and outflow of gas through the connecting passage exert an influence on the mixture formation and the subsequent combustion. Furthermore, many different chamber shapes are now employed and advantage claims are made for all of them without fully satisfactory explanations.

In the present investigation, the flow pattern and combustion process in the

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swirl chamber were studied by means of high-speed motion pictures taken through the glass windows on a full-scale engine. The photographic evidence obtained was correlated with the performance test of the experimental engine and discussed along with it.

## II. Fuel injection and combustion in the swirl chamber

### 1. High-speed photographic observations

In order to observe the mixing process of fuel with air and the pattern of flame in the swirl chamber, a specially-constructed loop-scavenging two-cycle engine (cylinder bore/stroke: 80 mm/90 mm) was used. Both sides of the swirl chamber, as can be seen in Fig. 1, were closed with heat-resisting glass windows. The chamber was a cylindrical one with a diameter of 36 mm and a depth of 20 mm. The volume of the chamber was equivalent to 76% of the total compression volume, and the area ratio of the connecting passage to the piston area was 1.6%. In this construction, the maximum velocity of air in the passage way during the compression stroke attains 200 m/sec at an engine speed of 1,200 r.p.m. For this experiment, Diesel fuel of cetan number 72 was used in order to give normal ignition delay in the relatively low compression-ratio engine employed (18 : 1 for the full stroke). Fuel was delivered by a Bosch-A-type injection pump PE1A50B101, with the quantity of fuel injected per stroke adjusted to 15-18 mg, corresponding to that injected at full load of this engine. The opening pressure of the injector was always set at 100 kg/cm$^2$. The camera used was the Hitachi high-speed motion picture camera (with maximum speed of 2,500 frames per second), or the Fastax FW-3 camera (with maximum speed of 8,000 frames per second). The combustion chamber was illuminated from the side opposite to the camera with such a light intensity that the patterns of both fuel spray and flame could be harmoniously photographed on the same film.

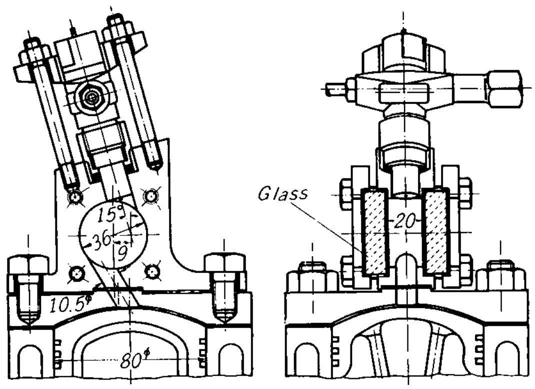

Fig. 1 Apparatus for photographing combustion in the swirl chamber

**Fuel injection through a single-orifice injector:** In order to investigate fundamentally the influence of the direction of fuel injection, fuel was injected through single-orifice injectors having different jet angles. Several examples of

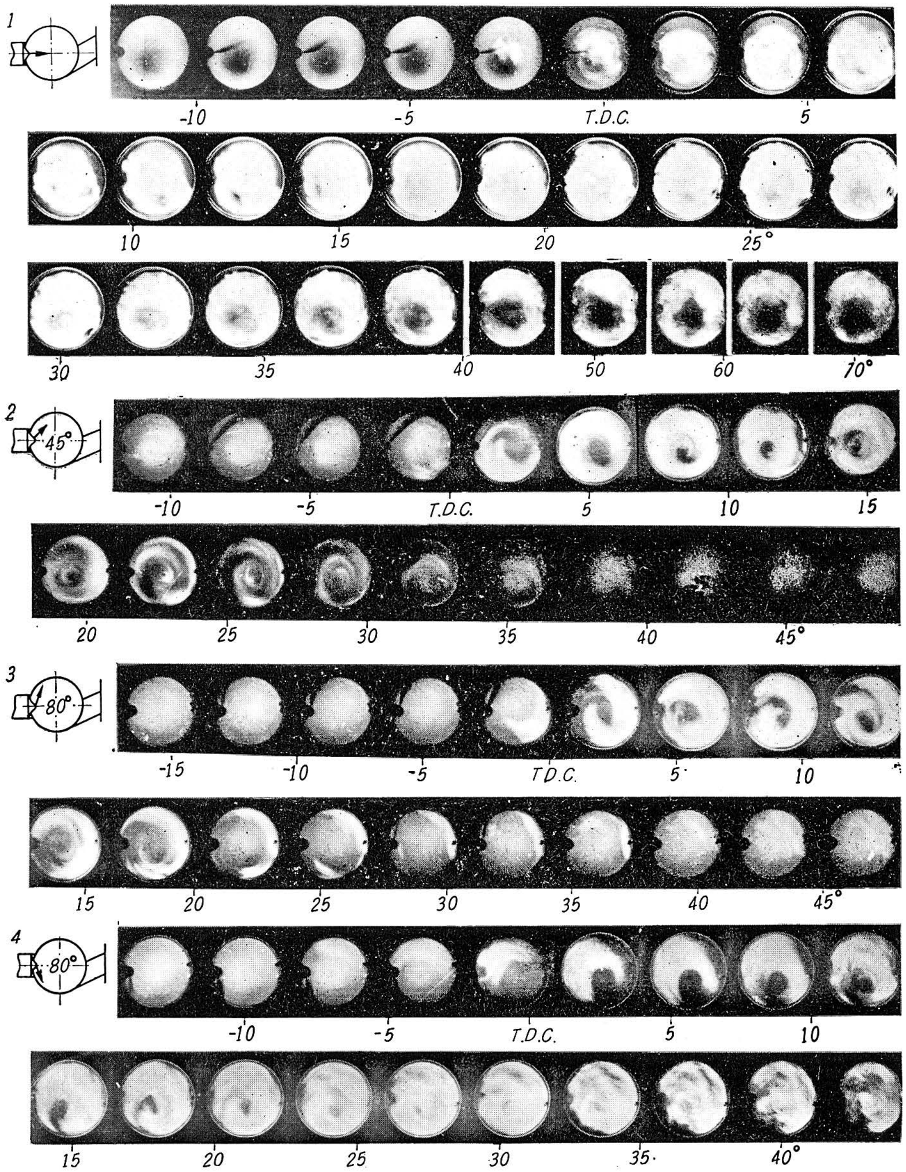


Fig. 2 Examples of high-speed photographs in the swirl chamber for the various cases of fuel injection through a single-orifice injector

| No. of film | Engine speed (r.p.m.) | Quantity of fuel injected per stroke (mg) | Diameter of orifice (mm) | Frequency of picture (frames/sec) |
|---|---|---|---|---|
| 1 | 1,250 | 18 | 0.30 | 3,550 |
| 2 | 1,130 | 17 | 0.35 | 2,020 |
| 3 | 1,040 | 17 | 0.35 | 1,860 |
| 4 | 1,000 | 17 | 0.35 | 1,920 |

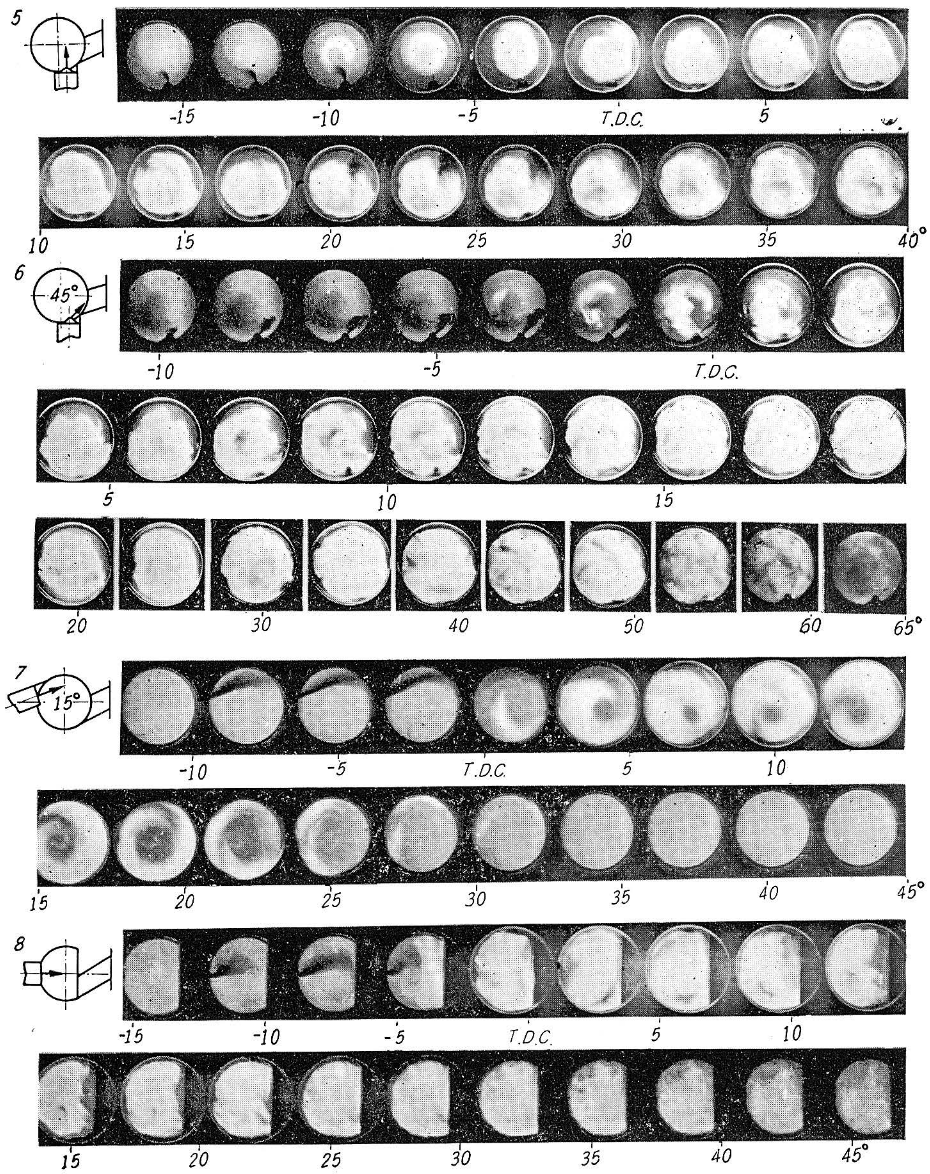


Fig. 3 Examples of high-speed photographs in the swirl chamber for the various cases of fuel injection

| No. of film | Engine speed (r.p.m.) | Quantity of fuel injected per stroke (mg) | Diameter of orifice (mm) | Frequency of picture (frames/sec) |
|---|---|---|---|---|
| 5 | 1,110 | 18 | 0.30 | 1,860 |
| 6 | 1,280 | 16 | 0.35 | 4,840 |
| 7 | 1,230 | 15 | (DN15S3) | 2,440 |
| 8 | 1,200 | 15 | (DN15S3) | 2,240 |

photographs taken are shown in film 1-6, Fig. 2 and Fig. 3.

In the case of injection from the upside of the swirl chamber toward the center of it (film 1), it is observed that the fuel spray is bent by a strong air-swirl blowing from side, and that ignition occurs first near the far end of the spray travel. The flame soon increases, and can be seen to rotate clockwise in the central part of the chamber. The portion of fresh air rotating in the peripheral layer is blown out first into the cylinder without participating in combustion there. A quantity of overrich mixture is therefore left in the swirl chamber until the combustion is nearly completed, resulting in soot formation. In the case of injection done through the injector with a jet angle of 15° downstream or upstream, the combustion process closely resembles the above, except that there appears a small flameless area in the midst of the chamber in the former and the amount of soot is increased appreciably in the latter.

In the instance when the injection is directed downstream with a jet angle of 45° (film 2), the fuel spray is carried together with an air-stream toward the passage, there meeting with a hotter air-stream simultaneously flowing in from the cylinder. Ignition occurs there at once, then the flame spreads rapidly over all the peripheral area. The middle area of the chamber remains quite flameless in the early stage of combustion. During the process of combustion, the rotating flame in the periphery is dragged spirally toward the center of the swirl, then fills the entire chamber, as has already been pointed out by F. Pischinger and A. Pischinger[3]. In this case, the rich mixture is entirely removed from the middle area of the chamber, and is transferred quickly into the cylinder with little resulting soot formation.

In the case of injecting downstream with a jet angle of 80° (film 3), the fuel jet reaches the chamber wall at an acute angle, and spreads like a thin film on it with the aid of an intense air-stream. A small portion of fuel, which is blown away from the fuel jet directly into the air, ignites first in the downside of the chamber. Following ignition, the combustion zone enlarges along the chamber wall, but in this instance, the center of the combustion chamber is never entirely filled by flame. This is explained by the injection pattern whereby the fuel is injected on the chamber wall, evaporates from it and burns near it, never dispersing to the center of the chamber.

In the case of injection done upstream with a jet angle of 80° (film 4), a greater portion of fuel is blown back together with the air-stream, and the rest adheres to the chamber wall. Ignition starts near the injector, then the flame spreads gradually to the entire chamber and considerable soot formation is incurred.

Comparing the rate of soot formation observed in each case, it is noted that the rate depends to a large degree on the direction of the fuel jet against the air-swirl. The maximum rate is attained when the injection is done upstream at 45°.

In the case of injecting fuel downstream at 15° from the vicinity of the connecting passage, similar combustion process as in film 1 was observed, except flame enlarged to a greater portion of the chamber space from the start of combustion, for the stronger air-swirl made the fuel spray scatter more intensely. In the case of injection done at 0° or downstream at 15° (film 5), the fuel spray is bent by a strong air-stream and transferred to the central part of the chamber. Then ignition occurs there, and the slow combustion takes place, resulting in intense soot formation in the chamber.

Film 6 is an example of a picture taken at a higher frame speed. Fuel is injected against the air-stream coming in from the cylinder through the passage way. Finer particles of the fuel jet are wafted back instantly to the upper part of the chamber, where they ignite after a very short delay. Within 1/2,000 second after the ignition, the flame fully consumes the fuel spray. The pattern of flame remains unchanged in its shape and continues to rotate in the middle part of the chamber; in this stage, little progress in mixture formation can be observed. This type of injection apparently results in poorer combustion and heavy soot formation. These results had been previously reported by Moore & Collins[2].

**Fuel injection through a pintle-type injector:** Further observations were carried out when the pintle-type injectors with several spray angles of 8°–30° were used. An example of photographs made during use of the injector DN15S3 is shown in film 7, Fig. 3. In the instance of injection done downstream from the upside of the chamber, a method which is found in the designing of most swirl chambers, fine particles of the boundary of the fuel jet are wafted off instantly and transferred together with the air-stream. The ignition is initiated near the connecting passage, and thereafter the flame spreads over the entire chamber space much more rapidly than when injection is done through a single-orifice injector. In all instances utilizing pintle-type injectors, the flame enlarges over all the peripheral area immediately after ignition. No appreciable accumulation of fuel in the middle of the chamber could be observed regardless of the direction of fuel injection; for the fuel spray in this case, owing to its weaker penetrating force, is customarily bent and dispersed by the air-swirl almost over all the perpheral area.

**Influence of the shape of the swirl chamber:** Another investigation was performed to examine the influence of the shape of the swirl chamber on the air-flow pattern in the chamber, which influenced greatly the combustion process. The swirl chamber with a flat-bottom was employed for this experiment. Film 8 (Fig. 3) shows an example of photographs in this chamber, in which fuel is injected through the same injector (DN15S3) used in film 7. By comparing this with the flow pattern in a circular chamber, it is appreciated that the damping of the air-swirl in the flat-bottomed chamber is effected to such a degree that the rotation of the flame grows weak rapidly after the combustion starts there, and that a core of the air-swirl is scarcely observable. In this case, the ignition is initiated in the downside of the chamber, and the flame spreads quickly upwards, then begins to flow out in order from the downside into the cylinder. In this chamber there were found to be no striking differences apparent in the combustion process with different directions of fuel injection.

Examination of the photographs in the preceding experiments leads to the following generalizations concerning the air-motion, mixture formation and combustion of fuel in the swirl chamber:

(a) In the strong air-swirl created in a circular chamber the penetration of fuel spray is weakened to nearly one-half that attainable in still air. Furthermore, when fuel is injected through a pintle-type injector, the boundary of the fuel jet is instantly blown away and then its core bent by an air-stream.

(b) The rotating motion of air in the swirl chamber, set up during the compression stroke, continues in the same direction nearly to the end of combustion, notwithstanding the fact that the outflow of gas has to a greater or lesser extent a reversing effect on the rotation. The rotating gas in the chamber flows out from the peripheral area, layer by layer, and thus the core of the swirl remains nearly to the end of the outflow from the chamber. This core of the swirl usually appears in the lower part of the chamber by TDC, and then revolves slowly in a clockwise direction round the center of the chamber, finally passing into the cylinder.

(c) If fuel is injected through a single-orifice injector toward the center of the chamber or upstream, the fuel accumulates in the middle space of the chamber where ignition is initiated. When combustion takes place, the local lack of sufficient air in the middle space results in much soot formation. On the other hand, if fuel is injected downstream at a suitable angle, fuel particles are transferred together with the air-stream toward the peripheral area. The first ignition occurs, in most cases, near the front of the connecting passage where the fuel comes into contact with the air of higher temprature. In this instance, since fuel is distributed over all the periphery, the rich mixture is able to flow out more rapidly into the cylinder, resulting in a quicker and smokeless combustion.

(d) The utilization of a pintle-type injector tends to prevent fuel from accumulation in the center of the circular chamber regardless of the injection direction.

(e) In the swirl chamber with a flat-bottom, the air-swirl is so rapidly suppressed after ignition that the rotation of the flame is scarcely observable.

**2. Experiments with a practical engine and their assessment**

In order to discuss the results derived from the high-speed photographic studies in relation to the performance of a practical engine, a four-cycle single cylinder Diesel engine was used. Its principal dimensions are as follows: cylinder bore/stoke 95 mm/115 mm, displacement 815 cc, compression ratio 16:1, fuel injection pump Bosch-A-type PE1A70B101.

Fig. 4 shows the cross-sectional view of the cylinder head of the experimental engine, the design of which permits either a spherical or a flat-bottomed chamber by changing the lower part of the chamber construction. The former chamber resembles the swirl chamber of the "Ricardo Comet-type III" and the latter the "type MK-V"[4] or the chamber of the Hanomag two-cycle engine[5]. For varying the direction of fuel injection different upper parts of the chamber were employed. The fuel used was heavy oil "A" (specific weight 0.85 at 20°C, cetan number 45).

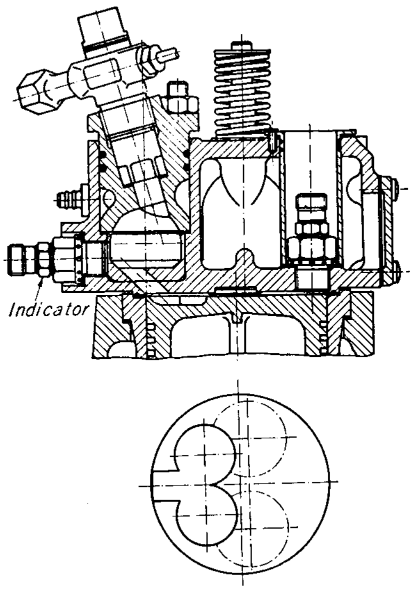


Fig. 4 Cross-sectional view of the combustion chamder for performance test

The comparative performance curves with different directions of fuel injection through the injector DN8S1 are collated in Fig. 5, in which it will be noted that the maximum power output and the fuel consumption, as well as the exhaust discoloration, become appreciably better as the direction of injection is shifted from upstream to downstream.

Fig. 6 illustrates a summary of the results obtained in the above two chambers with respect to three kinds of injectors (DN8S1, DN15S3, DN30S2). The maximum mean effective pressure was defined by the 60% of exhaust discoloration. It is interesting to note that the suitable direction of fuel injection differs to a greater or lesser extent according to the shape of the combustion chamber and the spray angle of the injector. In the spherical chamber, the best performance is obtained when injecting far downstream with a relatively small spray angle,

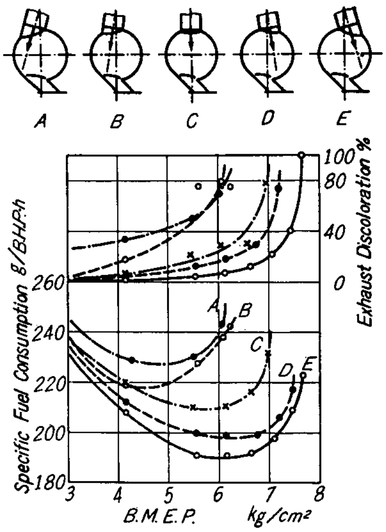


Fig. 5 Influence of the direction of fuel injection into the swirl chamber
Engine speed: 1,500 r.p.m., Injector: DN8S1 (opening pressure: 120 at), Cross-sectional area of the connecting passage: 2.0% of piston area

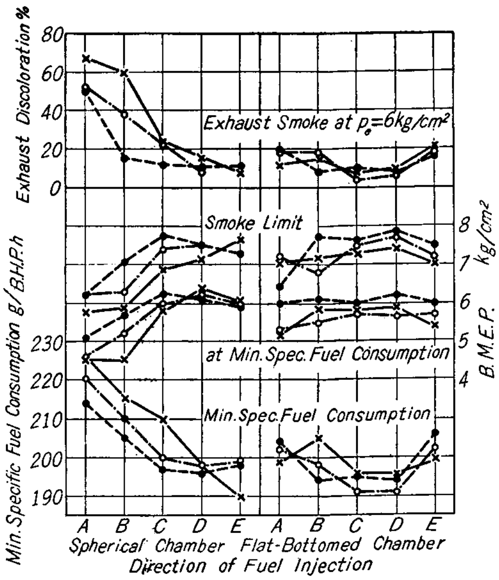


Fig. 6 Influence of the direction of fuel injection with different types of injector and of swirl combustion chamber
Injector: DN8S1 —— × ——
DN15S3 - - - • - - -
DN30S2 —·— ○ —·—

while in the flat-bottomed chamber the injection toward the center of the chamber is most favorable for good performance; moreover, the influence of injection direction upon the performance appears small in the flat-bottomed chamber. From a comparison of the performances with the two chambers, it will be evident that the optimum values in the maximum power output and the minimum specific fuel consumption obtainable in both chambers are nearly equal. However, the spherical chamber excels in the lower combustion noise while the flat-bottomed chamber shows advantages in cleaner exhaust and easier engine starting when cold.

In order to perform further study on the combustion state and combustion noise, pressure diagrams in both swirl and main combustion chambers, as well as the body-noise of an engine, were taken simultaneously with strain-gage type indicators and a microphone positioned 60 cm from the engine.

Several examples of indicator diagrams are shown in Fig. 7 and a summary of the mean values obtained from many diagrams is presented in Fig. 8. From this summary it will be observed that there is no appreciable difference in the period of ignition delay in the swirl chamber, except for the direction "E". The rise in pressure in the main combustion chamber increases as the direction of

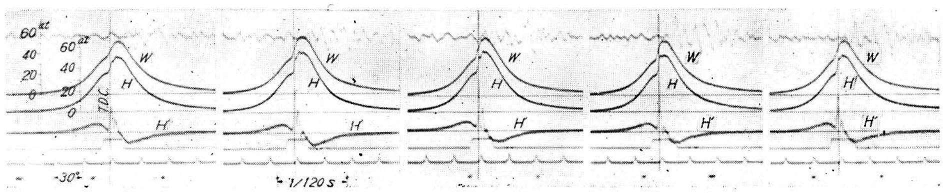

Fig. 7 Comparative indicator diagrams with different directions of fuel injection (taken in the spherical chamber)

Engine speed : 1,500 r.p.m., B.M.E.P. : 6.0 kg/cm², Injector : DN15S3, Connecting passage : 2.0% of piston area

Curves indicate from the above : Pressure in the swirl combustion chamber (W), pressure in the main combustion chamber (H), rate of pressure rise in the main combustion chamber (H′), fuel injection timing, and crank position.

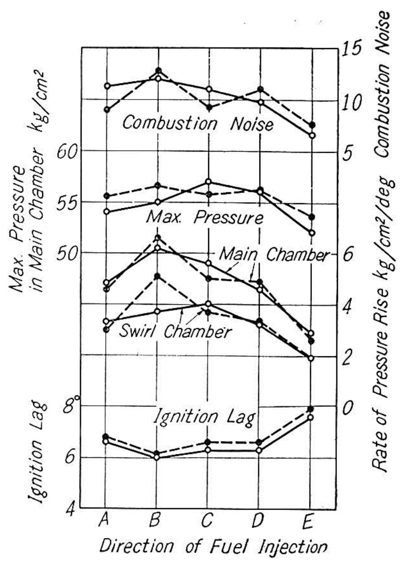


Fig. 8 A comparison of pressure variation with different directions of fuel injection (under the same conditions as in Fig. 7)

——o—— spherical chamber
– – –•– – – flat-bottomed chamber

injection shifts from downstream to upstream, attaining a maximum at the direction "B", where the amount of combusible mixture formed in the delay period is maximized. In constrast, at "E" the mixture formation is reduced to a minimum before ignition. The maximum amplitude of body-noise recorded on the oscillogram has the same tendency as the rate of pressure rise in the cylinder. It is interesting to note that the rate of pressure rise in the main combustion chamber, in all cases of injection direction, is larger than that in the swirl chamber, as may be clearly seen on the oscillograms of Fig. 7.

### III. Influence of the swirl intensity in the swirl chamber on the combustion

It is common to all engines with auxiliary combustion chambers that the engine performance is greatly influenced by the cross-sectional area of the connecting passage. In a swirl chamber type engine, this area is closely connected to the intensity of the swirl created in the swirl chamber during the compression stroke.

High-speed photographs were taken using both circular and flat-bottomed swirl chambers with several cross-sectional areas of the connecting passage. Fuel was always injected downstream with the center of jet passing about midway through the radius of the circular chamber, and the injector used was of the pintle-type

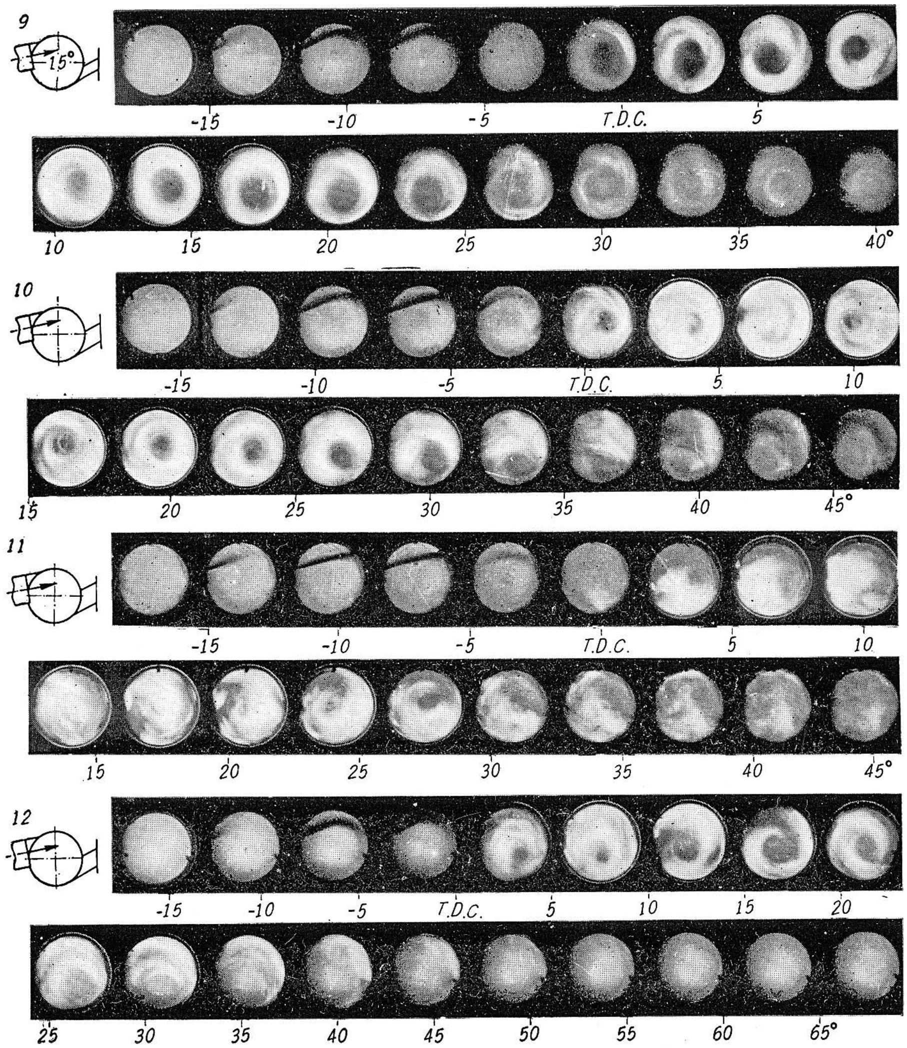


Fig. 9 Examples of high-speed photographs taken at various connecting passage area ratios, and taken at varying engine speeds

| No. of film | Area ratio of the passage (%) | Engine speed (r.p.m.) | Frequency of picture (frames/sec) | Characteristic constant $K$*) |
|---|---|---|---|---|
| 9 | 0.64 | 1,020 | 1,940 | $2.36\times10^{-2}$ |
| 10 | 1.26 | 1,050 | 1,960 | 4.38 |
| 11 | 2.24 | 1,000 | 1,770 | 8.40 |
| 12 | 1.26 | 1,760 | 2,310 | 2.68 |

*) $K=\frac{\mu f\cdot\sqrt{T_0}}{F\cdot c}$, where $c$: Mean piston speed (m/s), $F$: Area of piston surface ($m^2$) $f$: Cross-sectional area of the connecting passage ($m^2$), $T_0$: Temperature of air at the beginning of compression stroke (°K), $\mu$: Discharge coefficent (=0.65)

DN8S1.

Films 9, 10 and 11 (Fig. 9) show examples of photographs taken in the circular chamber having various connecting passage areas; their ratios ranged from 0.64 to 2.24% of the piston area. As the ratio of the area decreases, it is observed that the stronger air-swirl bends an injected fuel jet more sharply and transfers it downstream more quickly along the chamber wall. In this process, a part of the fuel adheres to the wall and is soon swept away on it downstream to the edge of the connecting passage, from which fuel is blown up again into the air. Ignition then takes place at once in the wider peripheral region of the chamber. This indicates that uniform mixture is more likely to occur rapidly in the entire periphery when the air-swirl is strengthened. Then, after ignition, the flame is ingulfed spirally into the nucleus of the swirl, thus the flameless area exhibited in an early stage at the center of the chamber is gradually filled by flame. The flameless area again increases in size at the center of the chamber, as combustion draws to a close. It is interesting to note that the flame pattern is formed in spiral, and that the number of its curls varies with the area of the passage area, i.e. with the intensity of the swirl. At the area artio 0.64% (film 9), the flame is composed of three curls; at 1.26% (film 10), two curls and at 2.24% (film 11), the flame is formed in a lump. In all cases, the swirling motion of air continues up to the completion of combustion in the chamber.

On the other hand, from the observations of the combustion process in the flat-bottomed chamber, it was clear that there is no striking difference in the process for different passage areas; the shape of the injected fuel jet is little changed by the area, and the nucleus of the swirl may seldom be noticed. The far end of the fuel spray arrives at the flat bottom of the chamber, and a part of the fuel adheres to the bottom wall and burns slowly near the wall until the end of combustion.

Films 10 and 12 (Fig. 9) show examples of the process in the circular with a constant passage area when engine speed is varied. It is interesting to note that there is found to be no appreciable difference in the ignition location and the flame motion, although the fuel jet is curved more sharply with the increase in engine speed.

Fig. 10 shows the comparative performance curves of the experimental engine when employing the spherical chamber and the flat-bottomed chamber, with different cross-sectional areas of the connecting passage. The tests were carried out under the most excellent conditions of fuel injection that were given for each chamber in Fig. 6. It is, to the authors, somewhat surprising to find that, with the decrease in the passage area, both specific fuel consumption and

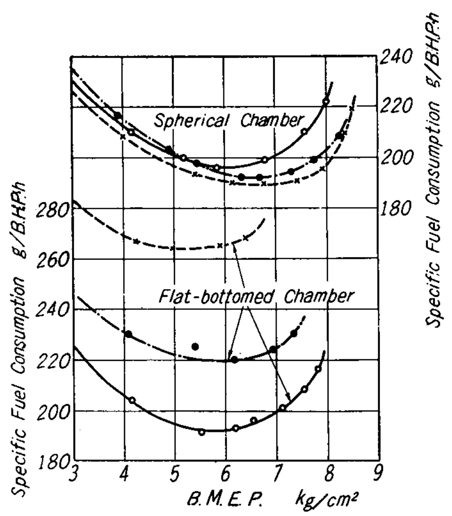


Fig. 10 Influence on the performance of the cross-sectional area of connecting passage in the spherical and the flat-bottomed chamber
Engine speed: 1,500 r.p.m., Fuel injection: spherical chamber; DN8S1, E, flat-bottomed chamber; DN15S3, D
--- × --- area ratio 2.0%
—•— • —•— " 1.5%
—— ○ —— " 1.0%

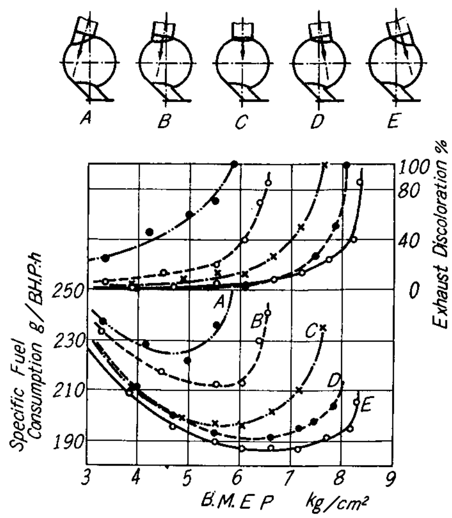


Fig. 11 Influence of the direction of fuel injection
Engine speed: 1,500 r.p.m., Injector: DN8S1 (opening pressure: 120 at), Cross-sectional area of the passage: 1.0% of piston area

output are appreciably improved with the spherical chamber, but are extraordinally worsened with the flat-bottomed chamber. In the latter, the smaller area of the passage is not more effective in strengthening the air-swirl, but results in an inherent increase in the heat and throttling losses at the passage and in retardation of the outflow of rich mixture into the main combustion chamber.

Fig. 11 shows the comparative performance curves with different directions of fuel injection into the chamber having a smaller passage area (1.0% of piston area). By comparing this figure with Fig. 5, it is apparent that an appreciable improvement on the performance is gained with the injections directions "C"—"E", while little improvement is obtained with the directions "A" and "B"; the difference in the performance according to the injections directions is therefore larger in this chamber than that having a larger passage area. With the injection direction "E", the specific fuel consumption continues to remain low up to the smoke limit and attains a minimum of 187 g/B.H.P.-h.

## IV. Some considerations on the effect of the thermal mixing in the swirl chamber

As has often been explained, the flame travelling in the perphery of the swirl chamber is ingulfed spirally into the midst of the air-swirl. This phenomenon may be explained as follows: When combustion begins in some part of the chamber, the gas density in this portion is suddenly decreased to at least 1/3 of that of the remainder. In turn, the centrifugal force of this portion of gas is decreased in proportion to the reduction of gas density, and subsequently the flaming portion of high temperature is pulled inwards. F. Pischinger and A. Pischinger have treated this phenomenon theoretically on the assumption that the swirling motion is a potential swirl, and were led to the interesting conclusion that the trace of the flame travel is entirely independent of the swirl speed; it is a spiral with a constant angle. They have named this phenomenon "thermal mixing" (thermische Mischung)[3].

In regard to the air-swirl actually produced in a swirl chamber, it is very difficult to find out the velocity distribution at the instant when ignition occurs. Nevertheless, it may be reasonably supposed that the characteristic of the swirl lies midway between a potential swirl and a rotation of a rigid-body. In any cases, no doubt exists as to the fact that the flaming gas is ingulfed toward the center of the swirl.

All the high-speed photographs had hitherto been taken from a position parallel to the axis of the cylindrical swirl chamber. Now, in order to examine the axial distribution of the mixture in the swirl chamber, the special apparatus was devised, which is illustrated in Fig. 12.

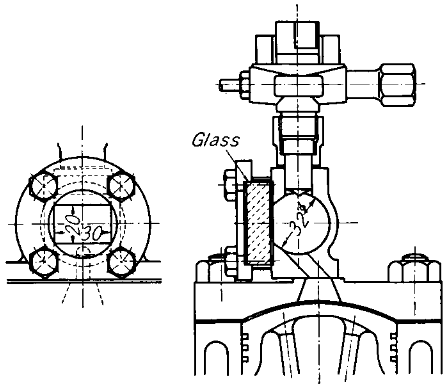

Fig. 12 Apparatus for photographing the axial distribution of the flame in the swirl chamber

Some examples of high-speed photographs are copied in Fig. 13. Film 13 shows the flame pattern when fuel is injected through a single-orifice injector at an angle of 45° downstream, and film 14 shows that for injection at 45° upstream. When the injection is directed downstream, the ignition location is observed to be in the middle part of the chamber axis. The flame soon spreads over the whole chamber, but fails to contact the side wall of the combustion chamber for a considerable period. On the other hand, when the injection is directed upstream, the flame area is expanded to both sides as the combustion process goes on, and continues to contact the side wall for a long period of combustion. Another notable difference between these two cases is the appearance of the flame; the former flame appears fibrous while the latter has a lump-like appearance. The

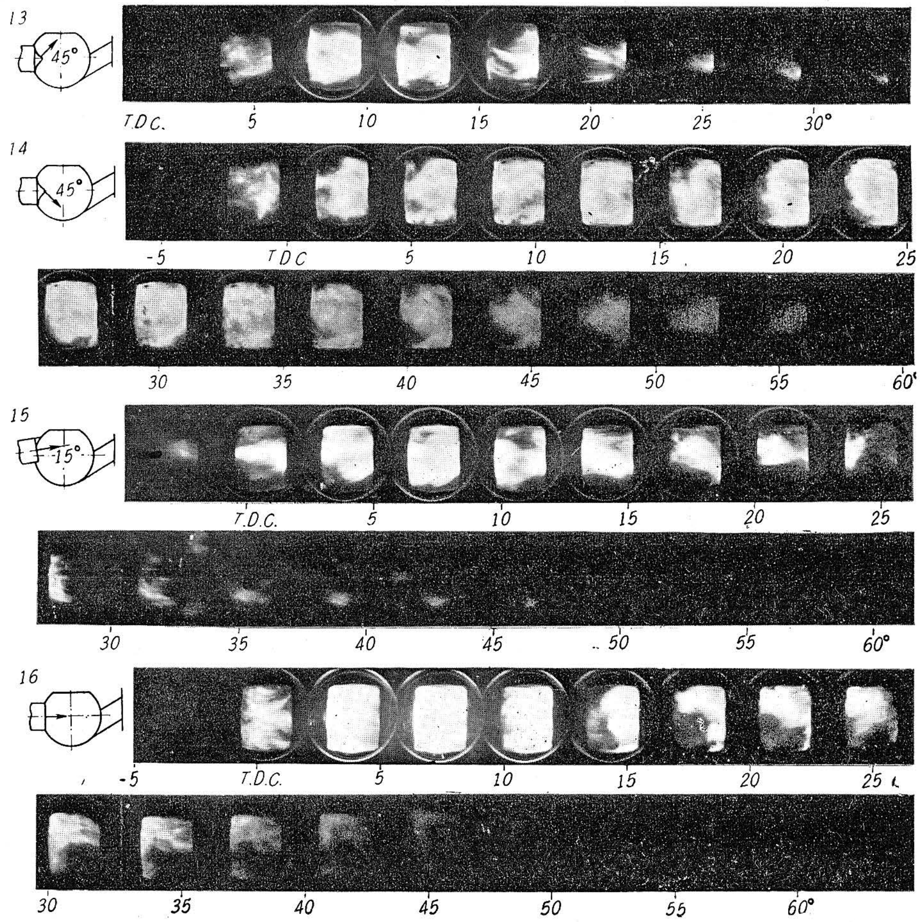


Fig. 13 Examples of high-speed photographs taken with the apparatus shown in Fig. 12

| No. of film | Fuel injection (injector, direction) | Engine speed (r.p.m.) | Quantity of fuel injected per stroke | Frequency of frames/sec |
|---|---|---|---|---|
| 13 | 0.35mmφ hole, 45° downstream | 1,120 | 13.0 mg | 1,840 |
| 14 | 0.35mmφ hole, 45° upstream | 1,130 | 13.0 | 1,970 |
| 15 | DN8S1, 15° downstream | 1,100 | 17.5 | 1,820 |
| 16 | DN30S2, toward the center | 1,160 | 13.0 | 1,780 |

duration of combustion differs to a great extent according to the injection direction, in spite of an equal quantity of injected fuel. These results agree well with those previously obtained by the photographs taken from the axial direction.

Film 15 shows the flame pattern when a larger amount of fuel is injected downstream through the pintle-type injector DN8S1. From the fibrous appearance of the flame, it may be deduced that the flame is travelling fast in the peripheral layer of the chamber. Furthermore, in this instance, it is worth noticing that the flaming zone reaches the side wall only temporarily.

The other photograph was taken when a pintle-type injector with a wide spray angle (DN30S2) was used. In this case, as can be seen in film 16, it is noted that the flame pattern appears in the entire combustion chamber from the beginning of combustion, because this injector yields a better distribution of the mixture during the period of ignition delay. This is considered as an essential difference apparent between film 14 and 15.

From examinations of this series of photographic studies, it has been clearly observed that the distribution of the injected fuel in the swirl chamber during the ignition delay depends primarily on the direction of injection, and that the inward travel of flame, owing to the nonuniformity in the gas density within the chamber, has an appreciable effect in improving the mixing of an overrich mixture with fresh air after ignition occurs.

Here, consideration will be given especially to the latter problem, "thermal mixing". When the fuel is concentrated into the peripheral layer of the swirl chamber, the combustion starts there, resulting in a decrease in the gas density of that portion. Subsequently, the portion of flaming gas is pulled toward the center of the swirl. This movement of the flaming gas forces the central portion of air toward both sides, following the outward movement of air near the side wall. This circulation of the gas stream permits fresh air to be continuously supplied to the combustion zone in the periphery. Summarizing the above processes, the formation of an overrich mixture in the periphery of the swirl chamber brings about two favorable factors for a rapid and complete combustion, one is the possibility of an earlier outflow of the overrich mixture into the cylinder; the other is the most effective use of the thermal mixing effect. For these reasons it is understandable that the fuel injection downstream brings about a superior combustion state.

On the other hand, when fuel accumulates first in the middle space of the chamber, the flaming zone exists there from the beginning of the combustion process. This state is considered to be dynamically stable; the gas in the center cannot be transferred outwards, since the air locating in the periphery is heavier than the gas in the center. With the progress of the combustion, the flaming zone is forced to spread out sidewards. This situation in the flame distribution produces a more stable condition; the extension of the flame toward the periphery and the supply of the fresh air to the combustion zone both are suppressed. As an inevitable consequence, the outflow of an overrich mixture into the main combustion chamber is retarded, resulting in a slow and smoky combustion.

It has been a quite strange phenomenon that a dark skadow often appears in the flame area of the high-speed photographs (e.g. films 5 and 6 (Fig. 3)) only when the fuel injection is directed upstream of the air-swirl in the swirl chamber. This substance might easily be supposed to be free-carbon particles cracked from fuel, since the discoloration of exhaust smoke increases noticeably in this instance. However, even if the free-carbon particles are produced in the flaming zone, they should emit brilliant light under the circumstance of high temperature. It has been frequently reported in the literature that the brilliance of the flame increases considerably in the combustion process accompanied by strong soot formation.

Now, considering the fact that the flaming, overrich mixture stays long near the side wall, i.e., the glass window, especially in the instance when fuel is injected upstream, it might reasonably be explained that the free-carbon particles produced by cracking of fuel are cooled in the vicinity of the side wall, to such a degree that they look black, thereby throwing a dark shadow in the high-speed photographs.

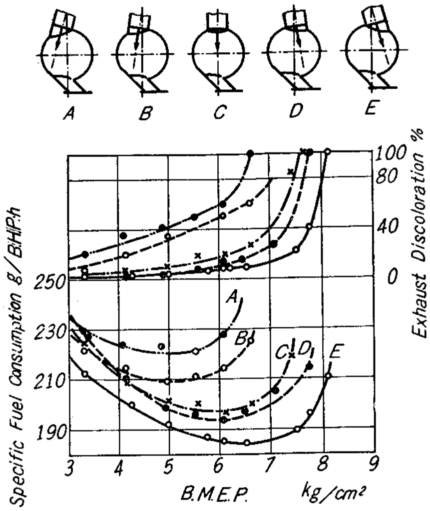


Fig. 14 Influence of the direction of fuel injection done with a very small spray angle
Engine speed: 1,500 r.p.m., Injector: DNOSD21 (opening pressure: 120 at), Cross-sectional area of the passage; 1.0% of piston area

Other experiments were carried out with a practical engine, in order to ascertain the validity of the above explanations. The performance test was tried when fuel was injected through the injector with an extremely small spray angle (DN0SD21) which suppressed the mixture formation during the ignition delay. Fig. 14 shows the comparative specific fuel consumption and output loops obtained at various directions of fuel injection. By comparing these results with those obtained with the injector DN8S1 (see Fig. 11), it is observed that the engine performance is somewhat poorer at the directions "C" and "D", while at the direction "E" the specific fuel consumption is further improved, attaining a minimum of 184 g/B.H.P.-h. From these observations, it will be understood that the thermal mixing effect is capable of accelerating the mixture formation and combustion after ignition occurs, and bringing the combustion to eariler completion despite the poorer mixture formation in the delay period of ignition.

## V. Influence of the piston crown cavity on the combustion

In order to determine the influence of the piston crown cavity on the mixing process of the half-burning products, which are transferred through the connecting passage, and the air within the main combustion chamber, high-speed motion pictures were taken using the apparatus shown in Fig. 15. The cavity employed for this experiment was similiar to the Ricardo-type, two cup-shaped depressions, positioned in front of the connecting passage. The volume ratio of the auxiliary chamber to the entire compression volume was equal to 50%, and the cross-sectional area of the passage was 0.78% of piston area.

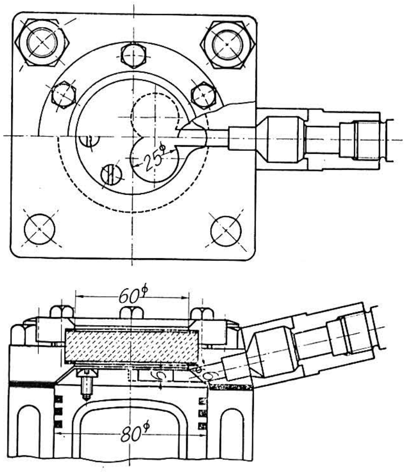


Fig. 15 Apparatus for photographing the combustion in the main combustion chamber

Fig. 16 shows an example of the flame pattern. The flaming gas jet expelled from the connecting passage soon arrives at the intersecting point of the two circular boundaries of the cavity, and is spilt into two

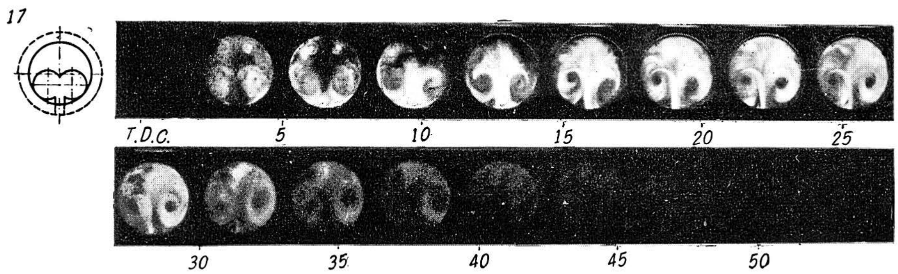


Fig. 16 High-speed photograph in the main combustion chamber with the Ricardo-type cavity
Engine speed: 1,210 r.p.m., Frequency of frames per second: 2,410
Fuel injection: DN4S24, 17.5 mg/st.

streams, creating two intense swirls in the cavity but in opposite direction. At the beginning of combustion, the flame is concentrated mainly in the cavity. As the piston drops, the flaming jet goes over the cavity boundary and then consumes the entire combustion chamber space almost uniformly. By comparing this process with that observed on a flat piston crown, it was clearly appreciated that the effect of the cavity is valid for improving the air utilization in the main combustion chamber.

Further experiments were undertaken to examine the actual effect of the

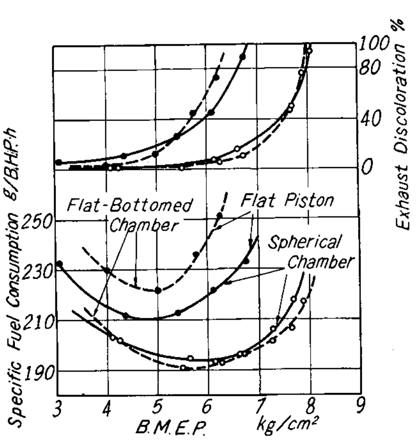


Fig. 17 Influence on the performance of the piston crown cavity
Engine speed: 1,500 r.p.m., Connecting passage: 2.0% of piston area, Fuel injection: spherical chamber; DN8S1, E, flat-bottomed chamber; DN15S3, D

piston crown cavity on the performance. Fig. 17 shows a comparison of the performance of the engine with the cavity or without it at the same compression ratio. From this it is apparent that the cavity has a large influence on the performance, and that the effective air utilization in the main combustion chamber takes care of an important function for improving the combustion state.

## VI. Improvement of the combustion in the swirl chamber type engine

From the results of experiments described above, it has been shown that the piston cavity has an important function for the combustion process in a swirl chamber system, especially, with a small chamber volume; i.e., the effective utilization of approximately one-half of the air which is retainded in the cylinder plays a large part in the combustion process. Hence, particular attention should be given to the outflow of the fuel from the swirl chamber.

As has been clearly observed in the high-speed photographs, the gas in the swirl chamber continues to revolve in the same direction, flowing out from the periphery, layer by layer. Accordingly, the bulk of fuel injected should be concentrated in the peripheral space and transferred into the cylinder as early as is possible.

Furthermore, it has been ascertained by this high-speed photography that the so-called "thermal mixing effect" handles a role in mixing of the overrich mixture part with the remainder of air after ignition starts; when the rich mixture is formed in the peripheral area where ignition is initiated. the flaming gases are ingulfed spirally inwards and subsequently mixed continuously with fresh air. On the other hand, when fuel is accumulated and the ignition is initiated in the middle space of the chamber, the flaming gases are extremely suppressed to be mixed with the air located in their surroundings.

By comparing the combustion process in the instance of injecting the fuel downstream with that of injecting upstream, a substantial difference between them may be noted. In the former instance, the fuel spray is transferred downstream together with an air-stream, producing a rich mixture in the peripheral layer. This state of fuel distribution is considered to be superior for the aforementioned two effects to permit a quicker and smokeless combustion. In constrast with this, in the latter instance, the fuel spray is bent toward the center of the chamber and then concentrated near there. The fuel therefore is left long in the swirl chamber with insufficient air. This results in a slow and smoky combustion. From these considerations is will be evident that the combustion process with the fuel injection directed downstream is much superior to that when the injection is directed upstream.

In addition, from the observations of the spray pattern by high-spped photography, and also of the fuel trace remaining on the chamber wall, it can be appreciated that a considerable amount of fuel, when it is injected downstream, comes in contact with the chamber wall before ignition, spreading over it like a film for a time. Shortly thereafter, part of the fuel evaporates from the wall and part is carried downstream on the wall by an air-stream. The stream then scrubs the fuel from the edge of the passage and disperses it again into the air.

By comparing the flame pattern observed in the flat-bottomed chamber with that in the circular chamber, it is interesting to note that the air-swirl in the former is weakened rapidly after the ignition starts. The outcome of this is a stagnation of gas near the chamber bottom and an outflow of gas which takes place in order from downside. It may therefore be understood that the influence of the direction of fuel injection on the distribution of mixture in the flat-bottomed chamber and the subsequent outflow into the cylinder becomes relatively small.

## VI. Conclusions

From the results obtained in a series of experiments on the combustion in a swirl chamber type engine, the following conclusions concerning the factors affecting the combustion process and the improvement of engine peformance were derived:

(1) In a spherical swirl chamber, the rotation of air set up by the tangential inflow through the connecting passage continues in the same direction nearly to the end of combustion, and the gas outflow into the cylinder takes place from the periphery, layer by layer. The fuel injected should therefore be concentrated in the peripheral area, so that it may be transferred earlier into the main combustion chamber.

(2) In a swirl chamber, there is evidence to show that the thermal mixing has an appreciable effect on the diffusion of the flaming gas and also the supply of fresh air into the flaming zone.

(3) The distribution of injected fuel in the swirl chamber, which depends primarily on the direction of the fuel injection against the air-swirl, has a great influence on the combustion process, and thus on the engine performance. When the injection is directed upstream, fuel particles are accumulated in the middle space of the chamber and subsequently are left with little air; this results in a slow and smoky combustion. On the other hand, the fuel spray, when injecting downstream, is transferred evenly with an air-stream, producing a rich mixture in the peripheral layer. This fuel distribution is most favorable for the effective utilization of the thermal mixing effect in the swirl chamber and also for earlier outflow of the overrich mixture into the main combustion chamber, which results in a quicker and smokeless combustion.

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