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Air Motion and Combustion in a Swirl Chamber Type Diesel Engine*

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According to the previous investigation on a swirl chamber type diesel engine, an earlier outflow of the fuel into the cylinder brings about favorable combustion. However, there appears a flameless region in the midst of the swirl chamber when the injection nozzle is so directed as to ensure the outflow action. In this paper, a better utilization of the air of this flameless area was aimed by controlling the air motion. Through comparison of engine performance together with observations of flow pattern and flame development, the following results were obtained: In the presence of a strong air swirl, the combustion is retarded owing to a poor mixture formation. A rather weakened swirl, which is realized by a proper selection of direction of the connecting passage or by slightly obstructing the stream, causes a better fuel distribution which assists the flaming in the central part of the chamber, thus resulting in an improvement in the engine performance.

1. Introduction

The mixture formation and combustion in a swirl chamber type diesel engine are largely affected by the intensity of air-swirl, as has been revealed by Ricardo's well-known research⁽¹⁾. On the other hand, one of the present authors reported that a correct direction of injection nozzle brought about a better spread of flame in the swirl chamber simultaneous with an earlier outflow of the fuel into the cylinder, thus giving a favorable combustion⁽²⁾: According to the high-speed photographs taken with an apparent swirl chamber, it is seen that in the case of injection nozzle located toward the center of the chamber an overrich mixture was formed at the middle space, resulting in a delayed outflow of fuel. On the other hand, when injected downstream, a rich mixture produced in the peripheral layer could quickly flow out into the cylinder, although it was noticed that the middle area of the chamber remained flameless. Therefore, the combustion state may still leave a room for improvement; the air of this flameless area may be more utilized without losing the operation

of quick transfer of the mixture into the cylinder. On the other hand, in the Comet Mk. V type engine, an increase in output has been achieved by adopting a swirl chamber having a flat bottom⁽³⁾. According to the photographic study, such a shape of swirl chamber showed a special feature that the air-swirl was very rapidly suppressed after ignition. This matter is suggestive of the concept that a proper control of the air-swirl may bring about a better utilization of the air existing in the swirl chamber simultaneous with maintaining an early outflow of the mixture into the cylinder.

In the present study, the air-swirl and its influences on the mixture formation and the subsequent combustion were studied from the above-mentioned viewpoint. At first, several attempts at controlling the swirl characteristics were made in the performance tests and then their functions were evaluated by means of water model technique together with high-speed photographic observations.

2. Air motion and engine performance

2.1 Test engine

For conducting performance tests, a four-stroke cycle single-cylinder diesel engine was used, whose principal dimensions were as follows; cylinder bore 95 mm, stroke 115 mm, swept volume 0.815 l, compression ratio 16:1, and fuel injection pump Bosch-A-type PE 1A 70 B 100. The swirl chamber was

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composed of two demountable parts as shown in Fig. 1, while the piston-crown cavity had, similarly to the Ricardo's Comet Mk. III type, two cup-shaped depressions positioned in front of the connecting passage. When the Comet Mk. III type chamber was employed with 51 % of volume ratio of auxiliary chamber to total compression space, the best performance was gained under the following conditions: area ratio of the connecting passage to piston surface was 1.0 %, injection nozzle pintle type DN 8 SI, its opening pressure 120 kg/cm², and direction of injection downstream at an angle 15° from the center of the chamber. In the present study, all tests were carried out under these conditions at an engine speed of 1500 rpm. The fuel employed was heavy oil "A" having a specific weight 0.845 and a cetane number 45. In all performance tests, injection timing was controlled so as to be optimum for each condition.

2.2 Direction of air-influx into the swirl chamber

With the ordinary configuration of the Comet Mk. III type swirl chamber, the connecting passage is so designed that during the compression stroke the air may flow into the swirl chamber along its wall. Indeed the air pushed into the chamber will get the largest angular momentum at the end of compression, but such a condition may bring about two possible by-effects. One is much heat loss due to the contact of a gas of high velocity with the wall surface; the other is the possibility of the early outflow of the mixture into the cylinder being obstructed on account of the relative location or direction of the connecting passage. In order to

evaluate the effects of swirl intensity itself as well as those of the related factors, five kinds of swirl chambers having the connecting passages with different directions were prepared, in which the air-influx was kept from the wall. Their detailed dimensions are shown in Fig. 2. With all types the angle between the connecting passage and the piston surface was intended to be equal, so as not to disturb the condition for the combustion occurring in the cylinder. Among them, the type I chamber, similar to the Comet Mk. III chamber, has a connecting passage tangential to the chamber wall.

Prior to the performance tests, the distribution of average temperature inside the swirl chamber was measured at motored condition with different directions of air-influx. Fig. 3 shows some results obtained. It is commonly observed that the contour-line is roughly concentric with a profile of the chamber, and that there is a ring-shaped hot zone

Fig. 1 Cross-sectional view of the combustion chamber for performance test

Fig. 2 Directions of air-influx and injection

Fig. 3 Distribution of average air-temperature in the swirl chamber (measured by a thermocouple at motored condition)

having a maximum temperature about 420 °C. It is true that with the direction III the temperature and its gradient at the peripheral layer are somewhat lower than those with I, but the degree of the differences does not seem so large as to have a definite influence on the heat loss through the chamber wall.

Fig. 4 shows the comparative effects on engine performance exerted by the above-mentioned designs of the swirl chamber, in the case of injection from the upside of the chamber toward an angle of 15° downstream from the chamber center. It is noted that the specific fuel consumption b_e becomes appreciably better as the direction of air-influx shifts from tangential to inner, and so with the exhaust discoloration under a light load. The best performance is gained with direction IV, in which the maximum obtainable bmep amounts to as high as 9 kg/cm². With direction V, the exhaust becomes badly discolored at lower bmep than with the original direction of I.

In the same figure is drawn the air-utilization factor ψ , that is, the weight ratio of air required for complete combustion of the introduced fuel to the air delivered in the cylinder⁽⁴⁾; this value is clearly a reciprocal of excess-air ratio and, if volumetric efficiency is constant, it is proportional to the weight of fuel introduced per stroke.

In connection with the direction of fuel injection, one must find out such a condition for excellent performance that the overrich mixture produced

somewhere in the swirl chamber might flow out early into the cylinder. This matter holds good in the case when the air-influx is directed inward. In Fig. 5 are shown the comparative performance curves in three different directions of fuel injection in the chamber with direction III. By comparing these curves, it is confirmed that the best performance is also gained when the injection is directed downstream. Further, it is noteworthy that the exhaust discoloration is less affected by the direction of injection under a light or medium load below 7.5 kg/cm² of bmep.

2.3 Projection placed on the chamber wall

In order to have a further knowledge on the damping of the air-swirl and its effect on the engine performance, an attempt was made to place a projection of various dimensions on the wall of the swirl chamber, the function of which was to control directly the swirl intensity. The projection was a crescent-shaped steel plate of 0.6 mm thickness, positioned in the chamber wall as illustrated in Fig. 6.

Fig. 7 shows the results of the application of this device to the chamber with direction I. It can be observed that both the specific fuel consumption and the exhaust smoke are considerably improved by fitting a projection of 2 mm or 3 mm, although the 4 mm-projection gives a somewhat poorer performance. With the suitable projection of 3 mm, the exhaust remains extremely clear up to a point very close to the maximum obtainable bmep, indicating a better combustion state than the original chamber (the case of 0 mm in the figure). In the next place, Fig. 8 shows the test results in the case when the similar projection is

placed downstream of the injector. It may be concluded that in this case the projection of any dimension has almost no advantage to performance. Further, performance tests were carried out for two other cases; one was the case when the similar projection was applied to the chamber with direction III, and the other the case of two projections placed on either side of the injector. As the result, little improvement could be achieved with either case.

Summing up the above test results, it is understood that the projection placed upstream of the injector is only good for performance. With a suitably dimensioned projection the exhaust becomes less discolored, whereas the one having an exces-

sive dimension again invites a poor combustion.

2.4 Local flat in the swirl chamber

As has been stated earlier, with the Comet Mk. V type engine, an increase in the power is attained by adopting a flat-bottomed swirl chamber. From the high-speed photographic study⁽²⁾, it was observed that in the flat-bottomed chamber the air-swirl once created during the compression stroke was very rapidly suppressed. If the key for the good performance of this type engine is really the quick damping of the air-rotation, caused by the peculiar shape of the chamber, then one may derive the same profit by flattening the chamber wall elsewhere. In order to clarify this, a lenticular

Fig. 6 Projection for obstructing the air-swirl in the swirl chamber

Fig. 7 Comparative performance curves with different dimensions of the projection when it is placed upstream of the injector

Fig. 8 Comparative performance curves with different dimensions of the projection when it is placed downstream of the injector

Fig. 9 Influence of the flat in the swirl chamber with direction II

piece of iron was fitted in the swirl chamber of type II at different locations as shown in Fig. 9, together with the performance curves with various positions and dimensions of the iron piece. It is noted that performance is unchanged or slightly improved under a light load by a small flat, while a large one fitted on the spray side shows a very poor performance, which is probably due to the fact that a greater portion of fuel adheres to the flat.

3. Analysis of air motion in the swirl chamber by means of water model

3.1 Basis of the analogy

To interpret the results derived from the above tests, some knowledges on the air motion produced in the swirl chamber and the differences resulting from slight changes in direction of air-influx or a projection are necessary in the first place. However, since a direct measurement of the flow pattern in the swirl chamber seems to be almost impossible at present, the authors approached their qualitative aspects by using a two-dimensional unsteady water-model.

It has been known that the motion of two-dimensional isentropic flow of a perfect gas with ratio of specific heats of two can be simulated by the flow of an incompressible liquid in a horizontal channel with a free surface, which was often used to study two-dimensional gas flows. In applying this technique to the analysis of air motion occurring in the swirl chamber now concerned, effects of viscosity that would play an important role in the creation and attenuation of the air-swirl must be neglected. Consequently, it will be difficult to discuss fully the microscopic currents such as would be produced at the position very close to the wall or the small-scale turbulence, so that the present analysis by means of the water model must be limited only to observe macroscopic events of the fluid. If this point is conceded, the one and only law for the simulation is that the Froude number of the water-model is equal to the Mach number of the corresponding gas flow. Therefore, let us take as reference velocities the mean piston speed c_m and the velocity of propagation of an infinitesimal wave at the end of compression a . When the mean piston speed can be related to revolutions per minute n and stroke S , we have

$$c_m = nS/30 \dots\dots\dots (1)$$

Hereafter every parameter concerned with the water-model will be affixed with a prime after the symbol. Then the mean piston speed of the model

is

$$c'_m = n'S'/30 \dots\dots\dots (2)$$

As regards the other reference velocities, a' is the function of water depth h' and a the acoustic speed of the gas. Thus the Mach number M and the Froude number M' can be expressed as follows.

$$M = nS/30a \dots\dots\dots (3)$$

$$M' = n'S'/30\sqrt{gh'} \dots\dots\dots (4)$$

where g denotes acceleration due to gravity. From the law of similarity $M=M'$, the running speed of the model is finally

$$n' = n \left(\frac{S}{S'} \right) \frac{\sqrt{gh'}}{a} \dots\dots\dots (5)$$

If the magnification factor of geometry of the model S'/S is 2 and the water depth at compression end $h'=0.05$ m, the running speed of the model must be 1.01 rpm at an engine speed of 1500 rpm where the acoustic speed is reasonably assumed to be 520 m/sec.

Fig. 10 illustrates the arrangement of water-model adopted for the present investigation. In this apparatus, the wooden piston and crank are driven quite similarly to the actual mechanism. The free-surface area of the swirl chamber was so dimensioned that the area ratio of this chamber to total surface at maximum compression might be the same as the volume ratio of swirl chamber in the test engine.

3.2 Direction of air-influx into the swirl chamber

Under the above-mentioned conditions, flow patterns were rendered visible by using aluminium powder as tracer, photographed by a 16 mm cine-

Fig. 10 Water model for investigating the swirling motion

camera. In Fig. 11 are shown the flow patterns gained at various conditions of the swirl chamber. Each curved line drawn in every picture indicates the motion of a fluid element from 20° to 15° before TDC, and its full length is therefore proportional to the average velocity of the duration; I, 2 and 3 show flow patterns with different directions of air-influx through the connecting passage. In every case, the rotation of air is nearly a stratified forced-vortex like the rotation of a rigid body. With the direction I, the nucleus of the rotation almost coincides with the center of the chamber, whereas with the directions II and III it locates somewhat upward. With the change of influx direction from tangential to inner, the swirling speed decreases considerably and so does in particular the velocity in the region at which the injector is directed.

3.3 Projection placed on the chamber wall

In 4 to 7 of Fig. 11 are shown the effects of a projection placed on the wall of swirl chamber. Owing to the experimental circumstances, however, the location of the projection is not exactly equivalent to that of the test engine. In the case of the 3 mm projection placed upstream of the injector (4), a circulatory current is observable behind the projection and the shape of the swirl is somewhat deformed. The motion of fluid is considerably slow, especially on the path line of the spray, compared with the case without a projection (1). As is observed from 5, these tendencies are more emphasized with the 4 mm projection. In the case of a projection placed downstream (6 and 7), the center of the swirl comes in the opposite direction, while the fluid accelerates the speed on the spray-path line. With the 4 mm projection, the swirl center so lifts upward owing to a big circulatory current, that a stream flowing from the projection

Fig. 11 Flow patterns in the swirl chamber

toward the connecting passage turns far more upward than with the 3 mm projection. In addition, 8 shows the case when two projection are simultaneously fitted both upstream and downstream. In this case, the swirling motion is scarcely observable in the middle space of the chamber.

From these observations, the pronounced features produced by the projection are summarized as follows: With the use of a projection placed upstream of the injector, the motion of a fluid at the right half of the chamber is weakened, while it is strengthened with the downstream projection. The projection having a dimension of order of 3 mm roughly halves the swirling speed, particularly in the peripheral layer. Since a considerably strong drag force acting on the swirl seems to be produced by the circulatory current behind the projection, the swirl will be damped much more quickly in this case at the expansion stroke than in the case without a projection.

4. Mixture formation and combustion observed by means of high-speed photography

As the effects of direction of air-influx and a projection on the air-motion were made clear through the above analysis, a further study was carried out by means of high-speed photography, taken through the glass window mounted on the swirl chamber, in order to reveal the mixing process of fuel with air and the subsequent combustion. For such a study⁽²⁾, the cylinder head of a loop-scavenged two-stroke cycle engine (cylinder bore: 80 mm; stroke: 90 mm) was reconstructed, as is shown in Fig. 12.

The swirl chamber was a cylindrical one with a volume equivalent to 80 % of the total compression volume (compression ratio 15.8:1). In order to simulate the less residual gas obtainable in a four-stroke cycle engine, the injection of fuel was made in every other revolution. A diesel fuel of 70 cetane number was used, in order to give normal ignition

delay in the relatively cold condition of the engine, and was delivered by a Bosch type injection pump PE 1 A 50 B 100, with the quantity of fuel injected per stroke adjusted to 21.6 mg, corresponding to that injected at full load of this engine (air utilization factor 63 %). The viewing camera was a 16 mm Shimadzu KS-16 high-speed camera. The swirl chamber was illuminated from the side opposite the camera with a suitable intensity of lamp light. Some examples of the high-speed pictures are collected in Fig. 13.

Films 1 and 2 show examples of the spray pattern and the combustion process when the direction of air influx is varied. With direction I, it is observed that the fuel spray is so diverted by the strong air-swirl blowing from the side that a greater portion of fuel reaches the chamber wall. In contrast, with direction III, the spray path is clearly kept apart from the chamber envelope. This difference is probably responsible for the lower intensity of the swirl. In both cases, the flame spreads rapidly over all the peripheral area after ignition and fills almost the entire combustion space. It is interesting to note that with direction III a curling flame reaches sometimes the midst of the chamber, while with direction I the middle area of the chamber remains quite flameless until the end of combustion. As can be commonly observed, the flameless area gradually increases as the combustion draws to a close. With direction III, the flame almost fades away between 20° and 25° after TDC. On the other hand, with direction I, a bright flame still remains in the periphery of the chamber at the same instant, and its complete extinction occurs at later than 35° after TDC. The most likely explanation of this would be that the outflow of the fuel into the cylinder is delayed owing to the adhesion of much fuel to the chamber wall.

Films 3 and 4 show examples of photographs taken when the projection is placed on the wall in the swirl chamber with direction I. Comparing these with Film 1, it is clear that with a projection the fuel spray is seldom swerved by the air-swirl and, at the same time, is less spread than in the case without a projection. The ignition is initiated near the tip of the spray, and then the flame gradually develops to cover all the chamber space. That the speed of the flame expanding to the maximum size is much lower in this case than under the condition without a projection may arise from the reduction of a mixture formed there during the ignition delay period. Some other remarkable features of the combustion

Fig. 12 Apparatus for photographing combustion

state are the strongly turbulent appearance of the flame and the absence of the flameless area that was seen in the original chamber (Film 1). Further, it is clearly noticed that the rotation of the flame varies largely with the dimension of the projection. At 3 mm (Film 3), the flame rotates slowly at first, but this does not continue up to the completion of combustion; at 4 mm (Film 4), the rotation of the flame is very weak from the beginning of inflammation and vanishes soon after TDC. In the latter case, it is interesting to note that the flame lasts for a very long period. This indicates that an excessive dimension of the projection will cause too early damping of the swirl, thus resulting in a poor combustion.

Examinations of the photographs in the preceding experiment lead to the following deductions concerning the effects of direction of air-influx

through the connecting passage and the projection placed on the chamber wall on the air motion, mixture formation and combustion:

(1) The fuel spray, the shape of which closely depends on the intensity of the swirl created in the chamber, finds its path nearer to the chamber center as the direction of the air-influx shifts from tangential to inner. When the air stream is obstructed by a projection placed upstream of the injector, the spray shape becomes straighter.

(2) When the direction of influx shifts with the varying position of the connecting passage, the flame is blown out early during expansion stroke. In this instance, the injected fuel is better distributed in the peripheral layer owing to the weakened swirl, thereby removing both the retardation of the combustion inside the swirl chamber and the delayed outflow of the mixture into the

Fig. 13 (1) Examples of high speed photographs

cylinder.

(3) When a projection is placed upstream of the injector, the rotation of the flame, which is strongly disturbed, attenuates very quickly. In this case, the weakened swirl does not blow off the fuel particles to the wall, ensuring a better distribution in the swirl chamber.

5. Air motion in the swirl chamber and the combustion

As has been observed above, a small change in the swirl motion will produce some variations

in the combustion state, thus bringing about a considerable difference in the engine performance. Generally speaking, in order to improve the performance of the divided chamber type engine, which the swirl chamber type engine belongs to, an outflow of the fuel from the auxiliary chamber into the cylinder should be done in the shortest period so as to obtain a perfect combustion in cylinder. The high kinetic energy of gas therefore has been considered to be an essential factor to the combustion therein⁽⁵⁾. Since, in order to produce a favorable circumstance, it is necessary to concen-

Film No.	Engine speed rpm	Frequency of frames per sec	Conditions
1	1550	5700	I : without projection
2	1390	5700	III : ibid
3	1410	5250	I : $d=3$ mm
4	1430	5930	I : $d=4$ mm

Fig. 13 (2) Examples of high speed photographs

trate the mixture near the connecting passage and also to produce a sudden pressure rise in the auxiliary chamber, the mixture formation and combustion must be so made in the swirl chamber as to produce a favorable condition of outflowing of the mixture, while at the same time the area of the connecting passage must be small enough to give a sufficient velocity to the outflowing gas. However, the optimum dimension of the connecting passage for outflowing does not always favor the mixture formation and combustion within the swirl chamber, owing to an excessive intensity of the resulting swirl. In such a mismatching condition, controlling the air motion in the swirl chamber would serve to make the combustion state well-balanced.

In our experiments, the swirl chamber with direction I without a projection was the case of mismatching; the injected fuel was strongly blown away by the intense air-swirl, thus coming very close to or on the wall of the chamber. Although the burned gas having a lower density was engulfed into the midst of the swirl⁽⁶⁾, by which the so-called "thermal mixing" process⁽⁷⁾ was made, the air in the middle of the chamber remained unused.

On the contrary, in the case with direction III or with a projection placed on the upstream side, owing to a rather weakened air-swirl, mixture formation and distribution enough to assist a better flaming in the middle of the swirl chamber were attained without sacrifice of an early outflow of the mixture into cylinder, thereby resulting in a better engine performance. Further, the case with the projection of 4 mm dimension was an example of poorer combustion caused by too early disappearance of the air-swirl, by which the mixture formation was injured. Such a condition led to a drop in the engine performance.

References

- (1) H. R. Ricardo: *The High-Speed Internal Combustion Engine*, (1951), Blakie & Son.
- (2) F. Nagao et al.: *Trans. Japan Soc. Mech. Engrs.*, Vol. 25, No. 160 (1959), p. 1324.
- (3) *Oil Engine Gas Turbine*, Vol. 25, No. 288 (1957), p. 130.
- (4) J. S. Meurer: *FISITA 10th Int. Autom Tech. Congr.* (1964), C-8.
- (5) F. Nagao et al.: *Trans. Japan Soc. Mech. Engrs.*, Vol. 24, No. 140 (1958), p. 240.
- (6) J. F. Alcock and W. M. Scott: *Proc. Inst. Mech. Engrs.* (A. D.), No. 5 (1962-63), p. 179.
- (7) A. Pischinger und F. Pischinger: *MTZ*, Jg. 20, Nr. 1 (1959), S. 5.

Discussion

M. YOKOI: (1) Concerning the state of swirl in a swirl chamber and especially the combustion characteristics in the middle part of the chamber, the obtained results in your study would be highly evaluated. However, taking account of both the excellent performance of Ricardo's Mk. V type chamber and the results in your study, the mixture formation in this type chamber may be also characteristic of the fact that fuel spray, transferred by air motion, impinges on the flat bottom or its edge, at which a strong turbulence is caused by controlling swirl speed. Please give your opinion on this point or experimental results, if any.

H. NAKAMURA: (2) In your study, it is reported that an increase in the output is attainable by properly damping the swirl inside the swirl chamber. Further, are there some common rules experienced in the series of your experiments?

(3) Please explain the correlation between the two-dimensional combustion chamber used for the high-speed photographic study and the actual three-dimensional one.

T. SAITO: (4) How are the maximum pressure and the rate of pressure rise dependent

on the type of swirl chamber? Please show some pressure-time diagrams, if any. How about the difference in combustion noise or in the related matters?

(5) In the case when a projection is placed, the region of a counter-swirl behind the projection (as seen in 4 of Fig. 11) is almost a dead space. How about the case when this space is filled up as shown in Append-Fig. 1?

S. Jo: I would like to appreciate the various experiments made to clarify effects of the chamber form on combustion in the swirl chamber.

(6) What is the similitude between the actual spherical chamber illustrated in Figs. 2 and 6 (con-

Append-Fig. 1

taining some modifications) and the two-dimensional model shown in Figs. 10 and 12? Hitherto, such a two-dimensional model has been often adopted for investigating the combustion inside the auxiliary chamber. Please show me the published paper about the propriety of this technique, if any, or the authors' opinion on this point.

(7) How would both the velocity of swirl and the fuel spray distribute in the spherical chamber in various cross-sections parallel to that of Fig. 2? Especially, to what extent would the form of the connecting passage affect these distributions (in the case when the dimensions of

are varied at a constant area)?

(8) In Append-Fig. 2, which illustrates a side view of the chamber in Fig. 2, is the air in the hatched region actually available for combustion? If so, please show me your opinion about its availability.

(9) In line 3 of the right column on page 841, you say "in order to improve the performance of the divided chamber type engine, an outflow of the fuel from the auxiliary chamber into the cylinder should be done in the shortest time, ..." But, I think that the swirl chamber, the volume of which is usually between 60 % and 70 % of the total compression space, has its objective to burn in itself the greater portion of the injected fuel. Further, if a too much fuel burns rapidly in the main chamber, an unnatural difference seems to occur between the two chambers, by which the gas flows backward into the swirl chamber, thus lead-

Append-Fig. 2

Swirl chamber : Ricardo Comet Mk. V type modified
Engine speed : 1500 rpm

Numerical number in each picture is crank angle of initial discharge measured from TDC

Append-Fig. 3 Flow patterns in a swirl chamber taken by means of repetitive discharge method (in which the striped pattern is successive reilluminations of discharge channels under application of repetitive high-voltage pulses ; rate of discharge 30 kc/sec)

ing to a drop in the output. Consequently, there will be a limitation to the earliness of the outflow of fuel into the cylinder, won't there?

Authors' closure

(1) It would be true that the impingement of the spray on the flat bottom is clearly one of the distinct features in the Comet Mk. V type chamber, but the blowing action upon a flat surface seems to have little advantage to the output and fuel consumption, as considered from Fig. 9. On the other hand, a turbulence produced in the bottom of this type chamber seems to have an important effect on combustion, as expected from the high-speed photographs in Reference⁽²⁾. In this connection, Append-Fig. 3 shows some examples of flow pattern taken by means of the electric discharge method^(a). From these pictures, it is observed that a considerable turbulence is generated in the bottom of the chamber.

(2) As has been described in the introduction of the paper, the purpose of the present study was to reveal whether the damping of swirl was generally effective for improving engine performance. From the obtained results, this rule was proved to be true. In addition, it was suggested that air turbulence was one of the factors governing the combustion process.

(3) It seems almost impossible to take a photograph in a three-dimensional spherical chamber. In order to remove this difficulty and at the same time to study the three-dimensional developments of the flame, a side view in a cylindrical chamber was once photographed and correlated with the results obtained with a two-dimensional one^(b). As has been reported previously, it was observed from a two-dimensional chamber that, when the fuel injection was directed upstream or toward the center of the chamber, fuel particles accumulated in the middle space thus producing a lump-like flame, and that, when injecting downstream, the flame continued to rotate and was dragged spirally toward the center of the swirl. The corresponding side views in a cylindrical cham-

ber are illustrated in Films 5 to 7 in Append-Fig. 4. When injecting upstream, it can be observed that the flame is expanded to both sides of the chamber and also has a lump-like appearance. When injecting downstream to the contrary, the flame having a fibrous appearance spreads itself to a small extent towards the chamber sides and is also engulfed into the center. From these results, it may safely be said that in tendency the combustion process in a two-dimensional chamber

closely resembles that in a three-dimensional one. Consequently, it can be concluded that such a two-dimensional chamber as presented in Fig. 12 may be available for observation purpose of the combustion state.

(4) No pressure-time curves was recorded with the test engine. Instead of this, examples taken at an equal fuel quantity from similar swirl chambers in a different engine are presented in Append-Fig. 5, in which I' and III' are the

Append-Fig. 4 Side views of the flame in the swirl chamber

Append-Fig. 5 Pressure-time diagrams of various types of swirl chamber

Append-Table 1
(Refer to Append-Fig. 2 for test conditions)

Type of swirl chamber	Peak pressure* kg/cm ²		Maximum rate of pressure rise* kg/cm ² /°		Specific fuel consumption g/PSh	Bmep kg/cm ²
	Swirl ch.	Cylinder	Swirl ch.	Cylinder		
I'	86.0	84.0	9.5	6.0	248	5.91
III'	72.2	66.3	3.5	3.2	229	6.51
Mk. V'	78.0	71.9	7.5	5.5	244	6.31

* indicates the average value from a few pressure-time cards.

chambers very similar to types I and III in the present paper and Mk. V' a modified Comet Mk. V type chamber. Append-Table 1 summarizes the measured peak pressures and maximum rates of pressure rise. Among three types, the rate of pressure rise is lowest with type III'.

(5) The first objective of fitting a projection was to produce microscopic swirls in the chamber, so that the adopted projection would not be the most adequate one for engine performance. The proposed one might be better under certain circumstances. However, a good performance could not be achieved in the case when upper and lower parts of the swirl chamber were not equal in inner sphere nor when there was a shear in their mounting.

(6) Indeed three-dimensional aspects are very important when treating the mixture formation and combustion, but in the air-inflowing process an approximation to a two-dimensional flow seems to be permitted since the axial velocity of the air stream may be negligibly small compared with its tangential velocity. To the authors' knowledge, no paper has been published on this subject.

As regards the combustion, please refer the reply to Mr. Nakamura's discussion.

(7) Probably nobody has made clear yet the fuel-distribution at various cross-sections of the swirl chamber, although that in a simplified two-dimensional chamber was already studied by the present authors^(c). After the authors' personal view, it seems impossible that the fuel distributes all over the chamber space, since, as the driving forces to distribute the fuel particles toward the chamber sides, there are merely the initial momentum given to each particle by the spray directions and the axial component of velocity caused by the air-inflow. In connection with this, the relation between length-to-breadth ratio of the connecting passage and the distribution, which is also unknown, may have something to do with the

Append-Fig. 6

fact that there is an optimum ratio for engine performance^(d).

(8) The authors' interpretation of the utilization of the air in the side spaces (hatched part in your sketch of Append-Fig. 2) is briefly as follows: Besides the principal swirl, generation of a secondary circulation as shown in Append-Fig. 6 may be associated with it. When fuel accumulates first in the middle space of the chamber, the flaming zone that exists there from the beginning of combustion is bound up by the centrifugal force of the swirl and is forced to spread out sideward, finally reaching a stable state. Therefore, there is almost no circulatory flow in this case. On the contrary, when the fuel is concentrated into the peripheral layer of the chamber, the portion of flaming gas is pulled toward the center of the principal swirl, and this movement forces the central portion of air toward both sides, thereby producing a secondary circulation. This circulation can permit fresh air to be continuously supplied to the combustion zone in the periphery. Probably these facts are related to a poorer performance experienced when a too wide spray angle is used or when the side spaces of the swirl chamber are cut away.

(9) As is pointed out by you, the presence of an excessive amount of fuel in the main chamber will invite a reflux of gas into the swirl chamber. As to the passage now concerned, please interpret it as removing such a state as to eject air only.

- (a) F. Früngel: *High Speed Pulse Technology*, Vol. II(1965), p. 162, Academic Press.
- (b) F. Nagao and H. Kakimoto: *Memoirs Fac. Engng. Kyoto Univ.*, Vol. 22, Part 2 (1960).
- (c) F. Nagao et al.: *Prep. 41st Annual Meet. Kansai-branch, Japan Soc. Mech. Engrs.*, No. 206 (1966), p. 25.
- (d) H. Nakamura: *Jour. Soc. Autom. Engrs. Japan*, Vol. 19, No. 1 (1965), p. 11.