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The Combustion Process in a Lanova Air-Cell Type Diesel Engine*

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High-speed motion picture taken through a glass window in a full-scale engine, has led to the following information as to the combustion process in a Lanova Diesel engine. The fuel supply into the cell, which depends principally on the fuel injection and the design of the air-cell, has a large influence on the engine performance. The fuel spray, if injected through the injector with a small spray angle toward the mouth of the cell, does not produce much mixture in the main combustion chamber before ignition, which burns slowly until the outflow of hot gases from the cell has improved the mixture formation to such a degree that quicker combustion becomes possible. These processes contribute toward a slow pressure rise in the early stage of combustion and high thermal efficiency. Furthermore, it was ascertained by the high-speed photography that ignition in the main chamber starts generally before that in the cell, and at the latest simultaneously with the ignition in the cell.

In an air-cell type Diesel engine in the early stage of development, combustion takes place solely in the main combustion chamber. The air-cell performs the additional function of supplying oxygen to the combustion zone in the main chamber. The kinetic energy of the outflow from the cell, under the above combustion system, is insufficient to create a swirl of air in the main chamber that can permit quicker combustion. In the Lanova air-cell type engine, which is now successfully employed, a considerable portion of fuel injected is delivered into the air-cell positively owing to the penetrating force of fuel jet, thereby producing a strong swirl effect in the main chamber. The combustion process in this type engine is therefore composed of many mechanisms, specifically, the supply of fuel into the cell, the mixture formation and the subsequent ignition, and the outflow of hot gases from the cell with their attendant creation of swirl in the main chamber.

Although there had been a number of research works dealing with the combustion in this type engine⁽¹⁾⁽²⁾, several questions remain unsolved, for

example, the place of the first ignition, i.e., whether in the main chamber or in the cell. From the results of our fundamental experiments on the effect of combustion swirl⁽³⁾, it can be easily inferred that the swirl created in the main chamber has an important function in improving the mixture formation and combustion in this type engine, and that the intensity of the swirl depends principally on the cell dimension and on the quantity of fuel trapped within.

1. Experimental engine

A loop-scavenged two-stroke cycle engine with crankcase compression was used for this experiment; its principal dimensions follow: Cylinder bore/stroke: 80 mm/90 mm, Compression ratio: 15.6:1, Maximum allowable speed: 3 000 r.p.m., Fuel injection pump: Bosch PE1A50B101. In this engine, as is shown in Fig. 1, the main combustion chamber with the circular section is located in the center of the cylinder head. The injector and the air-cell unit were exchangeable in their arrangement, so that the effects of the direction of fuel injection on the swirl effect could be investigated. The fuel used for this experiment was heavy oil "A" (specific weight 0.86 at 20°C, cetan number 45).

The pressure in both main chamber and air-cell was simultaneously measured with two sets of

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strain-gage type indicators mounted flush with the walls of the chambers.

2. Influence of fuel injection and of air-cell dimensions upon the engine performance

At the outset of experiment, the performance of the engine with the air-cell and injector arrangement illustrated in (I) in Fig. 6 was studied.

Influence of fuel injection

Fig. 2 shows the influence of the spray angle of a pintle-type injector on the specific fuel consumption at a constant speed of 1800 r.p.m., but under varying loads. It is obvious that both fuel consumption and power output are most improved with a spray angle of 0° (DN0SD21) in spite of poor mixture formation in the main chamber, and that they gradually worsen with an increase in the spray angle. These results appear very illuminating in that only a small portion of fuel,

Fig. 1 Cross-section of the combustion chamber of the experimental engine

Engine speed: 1800 r.p.m.
Volume ratio of the air-cell: 20.5 %
Area ratio of the neck: 0.36 %
Opening pressure of the injector: 90 at

Fig. 2 Influence of the spray angle of the injector

if it is injected with a wide spray angle, can be delivered into the air-cell, thus resulting in weakening the swirl created in the main chamber. From these results it is apparent that the spray angle of injector is one of the important factors affecting the distribution of fuel in the two chambers.

Fig. 3 shows the influence of the opening pressure of the injector (DN0SD21) that gave the most excellent performance in the above experiment, upon the performance as well as the characteristics of combustion. Both the maximum output and the minimum specific fuel consumption are attained at the injection pressure of 80 kg/cm². The maximum of the peak pressure in the cell is reached at a certain pressure, but that in the main chamber becomes higher and then somewhat exceeds the peak pressure in the cell, as the injection pressure is lowered. At the lower injection pressure the ignition starts first in the main chamber, while at the higher pressure the mixture ignites within the air-cell first. From these results it can be noted that fuel supply to the cell is quite sensitive to the opening pressure of the injector.

Influence of the shape and dimensions of the air-cell

Engine speed: 1800 r.p.m.
Volume ratio of the air-cell: 17.6 %
Area ratio of the neck: 0.25 %

Fig. 3 Influence of the opening pressure of the injector (DN0SD21)

As the first step, the influence of the cross-sectional area of the neck of the cell (or the connecting passage between the main chamber and the cell) was examined in the cell with a constant volume. Fig. 4 shows a comparison of the engine performance and of the values obtained from the indicator diagrams, in which it is noted that the most favorable area for the fuel consumption is somewhat above 0.25 % of piston area, while that for the output is somewhat smaller than the above area ratio. When the area of the neck is very small, the peak pressure becomes extraordinarily high in the air-cell, but lower in the cylinder; the pressures in both chambers approach a common point as the area increases. The maximum of the rate of pressure rise in the cylinder is attained at the same area ratio at which the maximum output is obtained, but this value of 3.5 kg/cm^2 is not so high as that observed in the other types of Diesel engines with auxiliary chambers. The area of the neck is indeed one of the important factors affecting the performance, for the key factor, the required amount of fuel to be supplied into the air-cell, could be controlled to some extent by varying the fuel injection timing.

As the next step, the influences on the engine performance caused by different air-cell to total

Engine speed: 1800 r.p.m.
Volume ratio of the air-cell: 20.5 %
Injector: DN 0SD21 (opening pressure: 90 at)

Fig. 4 Influence of the cross-sectional area of the neck

compression volume ratios were examined by using air-cells of different volume and a constant neck. In this case the volume ratios were varied from 12.0 to 22.4 % under a constant compression ratio. From the results obtained it is noted that there are no striking differences in either fuel consumption or output, since an adequate amount of fuel, appropriate to the cell volume, can be delivered into the cell by varying the injection timing.

The air-cell in most of the engines which are now successfully employed is divided into two compartments separated by an orifice. These two cells are called, for ease of identification, the ante-cell and the main cell respectively. A comparison was made on the engine performance for three kinds of cell units, which had, respectively, orifice diameters of 4 mm and 6 mm, or no orifice. Apparent effects of subdividing the cell can be observed only in the cell having a comparatively great volume (22.4 % of the total compression volume); the smaller cells fail to show definite results. From the experiment it is deduced that subdividing the cell will be helpful to avoid an oversaturation of the main cell with fuel, as has been explained by Fichtner.

Summarizing the preceding experimental results, there are no striking differences as to the influence of different cell dimensions on the engine performance, so long as an adequate of fuel is supplied to the cell by correctly timed injection.

Engine speed: 1800 r.p.m.
Volume ratio of the air-cell: 20.5 %
Area ratio of the neck: 0.25 %
Injector: DN 0SD21 (opening pressure: 100 at)
(d); The neck is deflected inwards at an angle of 20°

Fig. 5 Influence of the shape of the cell-mouth

Fig. 5 compares the specific fuel consumption and output using several forms of cell-mouth. The enlarged conical part of the mouth, as seen in (b), will to a certain extent ensure smooth and sufficient delivery of fuel into the cell. The results obtained show the increase in fuel consumption under a light load.

Influence of the relative directions of fuel injection and swirl in the main chamber

Fig. 6 shows a comparison of the engine performance with different arrangements of the injector and the cell unit, in which the location of the injector can be varied relatively in the swirl rotation of the air. Both fuel consumption and output obtainable are better in the order of (I), (II), (III). The fundamental experiment on the effect of the combustion swirl showed that the better results were obtained when fuel was injected downstream, not upstream. In this instance, however, the supply of fuel to the cell depends to a greater extent on the arrangement of cell and injector; in arrangement (I) the core of fuel spray can pass through the main combustion space and enter the cell directly; on the other hand, in (II) the supply of fuel to the cell is decreased, since fuel particles already dispersed are transferred there only indirectly by an air-stream.

Other experimental results on the effect of the swirl are presented in Fig. 5. The outflow of gas from the cell is directed at an angle of 20° downwards in (c), or inwards in (d). It appears in (c) that the fuel consumption under heavy loads is improved as compared with that in (a), whereas a considerable increase of the fuel consumption is observed over the entire range of load in (d). These results suggest that the outflow aiming at the center of the circular chamber results in avoiding the creation of the smooth air motion as would be obtained by the tangential outflow of gas. In all cases, even a slight turning of the direction of the outflow has an important effect in preventing the injector from overheating.

3. Observation of the combustion process by high-speed photography

From the above mentioned experimentations, considerable information has been obtained as to the action of the Lanova-type air-cell. Further investigations were performed by means of high-speed photography taken through a glass window mounted on the topside of the main chamber. For this experiment the HITACHI KPC-25 type high-speed motion picture camera (with maximum

Engine speed: 1800 r.p.m.
Volume ratio of the air-cell: 20.5 %
Area ratio of the neck: 0.25 %
Injector: I; DN0SD21, II, III; 0.45 mm ϕ -hole

Fig. 6 Comparative performance curves with different arrangements of the injector and the air-cell

speed of 2 500 frames/sec) was used, and the fuel spray before ignition was shown up by external illumination. Especially in this case, Diesel oil of 72 cetan number was injected in order to give normal ignition delay.

Examples of photographs are given in Fig. 7. Film 1 shows the mixture formation and the flame development in the main chamber when fuel is injected through a throttle-type injector with a spray angle of 0° (DN0SD21). The start of injection is at 10° before TDC. The fuel spray, which here appears white, is dispersed very little and has its core part passing through the main chamber to the cell-mouth, through which it enters. Immediately after TDC, ignition occurs initially in the main chamber; the spot of the first flame is located halfway between the injector and the cell-mouth. The flame soon consumes the whole of the spray, but in the early stage of combustion is limited to the left of the combustion space. At 10° after TDC, combustion occurs independently in the cell, and the outflow of hot gases begins to create a violent swirl clockwise in the main chamber; the flame spreads over the whole space and the combustion is accelerated rapidly.

Film 2 shows the combustion process for the case of comparatively earlier timing of injection (18° before TDC) through the same injector. The top of the core part of fuel spray arrives at the cell-mouth at about 13° before TDC, thus a greater amount of fuel is trapped in the cell owing to the stronger air-stream. Near the end of injection,

No. of film	Injector	Injection timing	Engine speed	Frequency of picture frames per second
1	DN0SD21	-10°	1 260 r.p.m.	2 380
2	DN0SD21	-18°	1 260 r.p.m.	2 370
3	DN8S2	-18°	1 330 r.p.m.	2 380
4	0.35 mm ϕ	-18°	1 180 r.p.m.	2 430

Quantity of fuel injected: 22 mg/stroke
Opening pressure of the injector: 90 at

Fig. 7 Examples of high-speed photographs

ignition starts in front of the cell-mouth and nearly simultaneously in the cell. The outflow of gases from the cell, in the first instant, takes place with a high energy. With progress of the combustion process in the main chamber, the pressure gradient between both chambers becomes considerably small, thereby causing the outflow to stop momentarily. The violent outflow is soon resumed, however, owing to the down stroke of the piston which again creates the swirl. In this case, a greater portion of fuel is delivered into the cell during the compression stroke, the rest of fuel burns up in the first stage of outflow, and the later outflow therefore resembles that in a pre-combustion type Diesel engine⁽⁴⁾.

Film 3 shows the combustion process when injecting through a pintle-type injector with a wide spray angle of 8° (DN8S2). Owing to the greater dispersion of fuel particles in the main chamber, only a small portion of fuel is sucked into the cell together with an air-stream. The first place of ignition is located near the injector in the main chamber, and then the flame zone enlarges to a considerable space in the early stage of combustion. The outflow of gases from the cell, however, seems to be delayed and weakened compared with that in film 1 or 2.

Other photographs were taken of the injector-cell arrangement shown in a dotted line, which corresponds to arrangement (II) in Fig. 6. An example is shown in film 4, in which fuel is injected through a single-orifice injector of 0.35 mm diameter toward the cell-mouth. The first ignition starts immediately in front of the cell-mouth, and then the combustion swirl is set up clockwise in the main chamber. The completion of combustion, however, comes somewhat later as compared with films 1 and 2.

From the above observations of the flame pattern, it is pointed out that the place of ignition, i.e., the spot of the first flame, is located always in the main chamber. Furthermore, when the injection is timed early and at a narrow spray angle, there is a tendency for the site of the first flame to shift toward the cell-mouth, and for the ignition in the cell instantly to follow that in the main chamber. On the other hand, it has been ascertained from many indicator diagrams taken in the performance test that the ignition in the main chamber starts at least simultaneously with the ignition in the cell, and generally before it except under extreme conditions of operation. These conditions are, for example, the high pressure of injection and excessively early timing

Engine speed: 2400 r.p.m.
Volume ratio of the air-cell: 15.0 %
Area ratio of the neck: 0.25 %
Opening pressure of the injector: 90 at
B.M.E.P.: 3.1 kg/cm²

Fig. 8 Relation between the ignition and the fuel supply into the air-cell

of injection.

4. Improvement of the combustion in a Lanova air-cell type engine

From the results of test as well as the photographic observations, it will be clear that the supply of fuel into the air-cell constitutes an essential part of mixture formation and the subsequent combustion, and is to a considerable extent influenced by the type of injector, pressure and timing of injection, and the shape of the cell mouth. In addition to these observations, it may be easily deduced that the amount of fuel trapped within the cell depends also on the distance between the injector and the cell, compression ratio, and the ignition quality of fuel. In one instance, in the event of ignition delay within a certain limit, the fuel spray will ignite before it has reached the mouth of the cell, resulting in a great decrease in the fuel quantity delivered into the cell.

Some experiments were made to check the relationship between the ignition and the fuel supply to the cell.

Fig. 9 Comparative indicator diagrams with different injection timings

(a) Fig. 8 (A) illustrates the comparative specific fuel consumption loops with two fuels of different cetan numbers. It is interesting to note that the difference in the fuel consumption of the two fuels appears comparatively small when fuel is injected through an injector with a small spray angle (DN0SD21); on the contrary, this difference attains a considerable magnitude when injecting with a wider spray angle (DN8S2). From these results it may be easily suggested that the fuel of high ignition quality, when it is dispersed within a short period of ignition, can barely reach and enter the cell, resulting in a decreased subsequent outflow energy from the cell.

(b) A coiled wire of nichrome was placed halfway between the injector and the cell-mouth, so that this heating element could be helpful to ignite fuel earlier. Fig. 8 (B) shows a comparison of the specific fuel consumption at a constant speed and load, with the wire or without it. In this experiment the fuel of cetan number 45 was injected through the injector (DN0SD21). It is interesting to note that the wire shows the effect of shortening the period of ignition delay in the main chamber and, as has been expected, the fuel consumption increases on the whole.

(c) Fig. 8 (C) shows the influence on the specific fuel consumption of the hot wire placed in the middle of the cell. In this case it turns out that the suitable timing of injection for the fuel consumption is entirely independent of the existence of the wire in the cell, but the fuel consumption is improved a little by the wire. From this it turns out that the wire is probably effective in advancing ignition in the cell, resulting in increasing the energy of gas outflow from the cell.

By the above investigations, it has been demonstrated that the combustion process in a Lanova-type engine depends primarily on the fuel supply to the cell and the subsequent combustion in the main chamber. Therefore it will be under-

Fig. 10 Characteristic of combustion at varying injection timings (under the same conditions as in Fig. 9)

stood that the performance of this type engine is more sensitive to the previously mentioned operating conditions than other engines of auxiliary chamber type.

Fig. 9 shows typical examples of the pressure diagrams in the cell and the main chamber with different timings of fuel injection, and Fig. 10 summarizes the characteristics of combustion at a constant speed and load. Although there appear only small differences in the fuel consumption over a wide range of injection timing (see Fig. 8), it is advantageous for the mitigation of combustion noise to make the timing as late as possible, as is indicated from Fig. 10. In this instance, when the timing is chosen a little earlier than the "limited" timing, after which the fuel consumption increases suddenly, the slower and lower pressure rise in the main chamber can be realized, resulting in quieter and smoother running.

Lastly, the best performance obtained throughout this experiment is summarized as follows: Maximum output; 12.5 B.H.P. (at 2700 r.p.m.), maximum B.M.E.P.; 5.0 kg/cm² (at 2400 r.p.m.) and minimum specific fuel consumption; 220 g/B.H.P.·hr (at 2400 r.p.m.). In this case, the volume ratio of the air-cell is 15%, the shape of the cell-mouth is as shown in Fig. 6 (b), and the cross-sectional area of the neck corresponds to 0.25% of piston area.

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