621.43.019.2:662.612

Influences of Direction of Fuel Injection and Wall Temperature upon Combustion in a Diesel Engine*

By Fujio NAGAO**, Makoto Ikegami***, Isamu Takagaki****
and Hiromu Konishi*****

The influences of direction of fuel injection and the temperature of the combustion chamber wall upon the ignition and the combustion process in the swirl chamber of a Diesel engine were investigated by means of high-speed photographs with indicator diagrams synchronized. The summary of results are as follows:

(1) Ignition of fuel is delayed by the cooling effect of the wall when the wall temperature is low, and this trend grows more remarkable as the direction of injection gets nearer to the wall.

(2) Duration of combustion is prolonged by increasing the concentration of fuel particles in the middle part of the chamber and by shortening the delay as well as by the increase of fuel adhering to the wall, which mitigates the rate of pressure rise due to combustion.

(3) When the fuel is injected along the wall, several features of combustion such as blue flame combustion, ignition from several positions and an abnormal shortening of the ignition delay were observed.

1. Introduction

The development goal for the combustion in a Diesel engine is to obtain a combustion system in which the fuel can be burned completely near the top dead center with a low combustion noise throughout the entire range of running. Referring to the direction of the fuel spray relative to the air swirl and the combustion-chamber wall with relation to the engine performance in a swirl-chamber type engine, performance is not as good when the fuel spray is directed against the air swirl, because the spray is apt to be concentrated in the central part of the combustion chamber, as observed in high-speed motion pictures in the previous paper⁽¹⁾. On the other hand, the effect of the chamber wall upon the combustion has been investigated by A. Pischinger u. F. Pischinger after constant-volume bomb tests under the condition similar to those occurring in the actual engine⁽²⁾. They have revealed that the influence of the wall temperature upon com-

bustion is decreased as the direction of the spray is changed from the wall toward the center of the chamber, and that, if the wall is hot and a sufficient air swirl is present, the injection along the wall causes a perfect combustion with a low rate of pressure rise in spite of poor interaction between fuel and air.

The aim of this study is to reveal the influences of both the spray direction and the wall temperature upon the mixture formation of the fuel and combustion process in an actual engine with a strong swirl in the combustion chamber. Observation was made mainly by means of high-speed photography with indicator diagrams synchronized. Further study was carried out to grasp the essentials of the combustion mechanism of so-called M-combustion system⁽³⁾ which has been characterized by an extreme utilization of the chamber wall and the air swirl.

2. Experimental apparatus

To visualize the progress of the mixture formation and combustion, a cylindrical swirl chamber with a specially strengthened glass window has been mounted on a loop-scavenged two-stroke engine: cylinder bore 80 mm, stroke 90 mm, and stroke volume 0.452 l. The combustion chamber has dimensions of 36 mm in diameter and 20 mm in

* Received 30th November, 1960.

** Professor, Department of Mechanical Engineering, Kyoto University, Sakyo-ku, Kyoto.

*** Student of Post-graduate Course, Department of Mechanical Engineering, Kyoto University.

**** Engineer, Mitsubishi Ship Building & Engineering Co., Ltd.

***** Engineer, Toyota Automobile Industry Co., Ltd.

width, as shown in Fig. 1. The volume ratio of the swirl chamber to the total compression volume was chosen as large as 86% so that the greater part of the combustion might be completed in it. The area ratio of the connecting passage to the piston area has been 1.72%, while the compression ratio being 19.0 and the effective ratio being 13.0. With this configuration, one can estimate the maximum air velocity in the swirl chamber attainable as high as 135 m/sec during the compression stroke, at an engine speed of 1250 r.p.m.

To remove the influence of the residual gas and to simulate the better scavenging efficiency obtainable in a four-stroke engine, the engine was fired in every other revolution, thus affording double scavenging to every power stroke. The amount of 17 mg fuel was injected for every firing stroke through a 0.35 mm ϕ -orifice injector at four different directions, namely 0-, 15-, 45-, and 80 deg., as shown in Fig. 2, the angle measured from the diametral line of the chamber toward the down stream of the swirl, which will be designated as the direction of the fuel injection. The fuel used was a Diesel oil of specific weight 0.785 and cetane number 72, and the injection pump was of Bosch type PE1A50B100.

The temperature of the chamber wall was controlled by a gas burner and measured with an Alumel-Cromel thermocouple inserted close to the wall surface, as shown in Fig. 1. Since the temperature distribution of the wall would be considerably influenced by the period of the motored and/or fired running, the measured wall temperature may

Fig. 1 Apparatus for photographing combustion

Fig. 2 Directions of fuel injection and swirl

only be used as a qualitative indication of the surface temperature. For this reason, time for preparation was made as short as possible to make the test conditions even. The maximum temperature attainable was 350 deg. C, which, limited by the use of a glass window, seems nevertheless sufficient for the practical engine.

A 16mm Hitachi KPC-25 type high-speed camera was used as a viewer, having a maximum speed of 2500 frames per second, which corresponds to about a hundred pictures per revolution of the engine shaft at a speed of 1250 r.p.m. In the photographed film marks of the timing and crank angle were recorded.

The indicator diagrams were single-swept on the cathode-ray tube of a dual beamed oscillograph equipment, in such way that they might be sampled among cycles that were taken by the high-speed camera. As the transducer of the pressure in the combustion chamber, a strain-gage type indicator (Kyowa Musen Co., Ltd., PHF-7B type), which has nominal natural frequency above 35 kc/sec, was attached to the chamber wall directly as shown in Fig. 1, for the sake of avoiding a harmful pressure vibration caused by any indicator passage. The injector needle motion was detected by a magnetic pickup, whose output was, after amplification, superimposed upon 0.1 kc/sec.-square wave for timing mark, then led to one of the Y-axes of the oscillograph. The crank-angle pulses of every 20 degrees were generated photoelectrically by a slit disk fixed on the engine shaft, and were recorded in the oscillograph as well as the high-speed camera. Fig. 3 shows the measuring system schematically, including a control unit to synchronize the indicator diagrams with high-speed photographs or to take

p: pressure in the combustion chamber,
l: injector needle motion,
c: crank angle,
s: signal for sweeping,
N: neon-indicators

Fig. 3 Schematic arrangement of apparatus

Fig. 4 Flame photographs

indicator diagrams alone.

3. Observation of combustion process

Typical flame photographs are given in Fig. 4, and corresponding indicator diagrams in Fig. 5 (numerical numbers are equivalent to those of Fig. 4), contrasting combustion processes of lower wall temperature (at about 150 deg. C) with those of higher wall temperature (at about 320 deg. C), for four different directions of fuel injection.

In the case of the 0 deg. direction (Films and Cards 1, 2): At the lower wall temperature, the flame spreads rapidly over the whole space of the combustion chamber immediately after ignition occurs, and lasts for a longer period with a bright light, to get out of shape in the later stages of combustion. The rate of pressure rise is high enough to cause a furious knocking. At the higher wall temperature, the ignition delay is somewhat short, thus affording a lower rate of pressure rise and peak pressure. The flame has a smaller spread than that of the lower wall temperature.

In the case of the 15 deg. direction (Films and Cards 3, 4): Ignition starts in the middle of the chamber in the case of the lower wall temperature, and in the vicinity of the wall near the connecting passage to where spray particles move in an arc, in the case of the higher wall temperature. The flame never ceases to rotate until its extinction,

in the meanwhile there is a dark space left in the center of the swirl. The flame is bright when the wall is hot. The duration of combustion is fairly short compared with that of 0 deg. direction, which will be shown in Fig. 6 as the result of measuring the photo-current of a transistor fronted to the combustion chamber.

In the case of the 45 deg. direction (Films and Cards 5, 6): At the lower wall temperature, ignition starts from about the middle part of the chamber, but in the vicinity of the wall at the higher wall temperature. In the latter case the flame appears bright and spacious. In both cases the flame moves spirally toward the center. No remarkable difference can be pointed out in the indicator diagrams, other than the ignition delay.

In the case of the 80 deg. direction (Films and Cards 7, 8): When the wall is at the lower temperature, ignition starts close to the connecting passage after a longer delay, and an initially dark flame with a slow pressure rise is followed by a regular blaze which accompanies the maximum rate of pressure rise, at about 6 degrees after TDC. At the higher wall temperature, no initial dark flame being present, the pressure rise is rapid at first but decelerated later. In both cases, the steady flame is dragged toward the center, and lasts for a longer period than in the case of 15- and 45 deg. directions.

From the above mentioned observation and other experimentations the followings have been deduced:

(1) In the case of a lower wall temperature, the ignition occurs belatedly, the possible location of initial flame, excluding the case of the 80 deg. direction, being at the center of the chamber to where fuel particles have been dragged. From several flame photographs it has been found that in general the nearer such a spot appears to the wall as the wall temperature increases.

(2) Immediately after inflammation, there exists a period in which the combustibles emit a faint light before the flame turns into a regular blaze. The period grows longer as the direction of the spray is varied from the center toward the wall, and becomes shorter as the wall temperature increases. This appears remarkably long with a lower wall temperature at the 80 deg. direction, and could be observed as a blue flame period by the naked eye, while for the other directions it could not be ascertained to be blue. In indicator diagrams, such a period corresponds to the very slow pressure rise at the foot of rapid ascending.

(3) Except for the 0 deg. direction, the flame continues to swirl without crumbling till its extinction. For the 80 deg. direction, the flame is dragged towards the center with one end fixed steadily upon

p : pressure in the combustion chamber,
 l : injector needle motion,
 Numerical numbers correspond to those in Fig. 4
 Fig. 5 Indicator diagrams

the wall. For the 0 deg. direction, however, the flame spreads out gradually from the center in the form of a cumulo-nimbus to cover the greater part of the chamber, changing into an irregular form in the final phase of combustion.

(4) The duration of visible light emission is long with 0-and 80 deg. directions, and short with 15- and 45 deg. directions. To inquire into this phenomenon, a photo-transistor was set in the position where the lens of the high-speed camera had been located, to measure the intensity-time trace of visible light emission. The results are summarized in Fig. 6, from which it can be proved that, for the constant wall temperature, the duration is shortest with the 45 deg. direction, while with the 0 deg. direction it is longest, and that, although the general tendency is the duration being increased with the wall temperature, there exist minimum points near 170 deg. C of wall temperature, in the case of 15- and 45 deg. directions.

(5) A finding concerning the maximum luminosity of the flame, also ascertained by measuring the photo-current, is that the luminosity increases as the wall temperature increases for a direction of injection and increases as the direction approaches the center of the chamber, as shown in the upper half of Fig. 6. No further conclusion, however, might be made out of the figure, because, besides the luminosity, the spread of the flame and the color-sensibility of the transistor must influence the photo-current considerably.

(6) Several indicator diagrams were taken besides the ones synchronized with flame photographs

Fig. 6 Duration of combustion and peak photo-current of the photo-transistor

such as Fig. 5. Measurement made with injection of the four directions and wall temperature ranging from 140 deg. C to 400 deg. C gives Fig. 7, which shows measured ignition delays, maximum rates of pressure rise and maximum pressures. First of all, the ignition delay is shortened with the wall temperature in every direction of fuel injection, and this trend is remarkable with the 80 deg. direction. In 0- and 15 deg. directions, considerable cycle-to-cycle variations are observed but held within the hatched domain in the figure. At a constant wall temperature, the rate of pressure rise increases definitely as the fuel is injected in more inward direction. An increase in wall temperature decreases the rate of pressure rise through the shortening of the ignition delay in the case of 0-and 15 deg. directions, but causes a little effect in the case of the 45 deg. direction, and in the meanwhile, it shows quite opposite tendency for the 80 deg. direction. At high wall temperature, the rate of pressure rise tends to a constant value in every direction. The maximum pressure shows more complicated nature. In the 0 deg. direction, the value, very large at low wall temperature, decreases rapidly with the wall temperature, while in the 80 deg. direction, it increases with the temperature. Other directions show intermediate trends between 0- and 80 deg. directions, and the 45 deg. direction gives the highest

Fig. 7 Effect of wall temperature upon ignition delay, maximum pressure, and maximum rate of pressure rise

value of all at the higher wall temperature.

4. Considerations

On ignition delay and location of ignition

J. Alcock & R. Watts have observed the combustion process in an engine with a transparent combustion chamber, by similar high-speed photograph technique.⁽⁴⁾ Some of their results are: (1) The fuel jet strikes the wall, and the resulting splash can spread some distance along the wall, playing an important part in fuel and air distribution, and (2) ignition occurs in small separate nuclei which never occur in the visible spray but usually near it or in the "wall splash".

Our observation does not conflict with these, although the behavior of the nuclei nor the splash cannot be observed because of the limitation of the camera speed. Some new facts, however, are contributing to them, namely, that, for any direction of the fuel spray, ignition occurs from the middle part of the chamber in the case of a lower wall temperature, but in the vicinity of the wall when it is hot, as described in the previous chapter. This shows that the fuel particles get more or less to the wall surface, and that, when the wall is sufficiently hot, ignition starts from the splash close to the wall, which has been heated up by the hot wall in grazing against it. Contrary to this, in the case of a lower wall temperature, the possibility of ignition is small, partly because the splash is cooled by the peripheral air stream which has been cooled

Table 1 Minimum temperature able to fire

Direction of injection	In the four-stroke operation	In the two-stroke operation
0 deg.	108 deg. C	94 deg. C
15	120	105
45	128	115
80	140	119

The values of four-stroke operation are derived from Fig. 7

Fig. 8 Comparison of ignition delays of two-stroke operation and four-stroke operation

by the wall at the upper reaches of the stream, and partly because the evaporation of the fuel adhered to the wall in the liquid phase is delayed by the cool wall surface. Consequently, ignition is apt to occur from the middle of the chamber to where the fuel is dragged, having been finely atomized and entirely heated up.

For 0-and 15 deg. directions at a lower wall temperature, as it takes long before the fuel reaches the opposite side of the wall, the effect of the wall temperature on the ignition delay is less than that for other directions, and minimum wall temperature that can cause a firing is consequently decreased as the direction of the injection is varied from the wall to the center, as shown in Table 1, in which the minimum temperature is given for the two-stroke operation as well.

In addition, Fig. 8 shows the ignition delays of the two-stroke operation, where the same amount of the fuel has been injected per engine revolution, setting forth evidently that the residual gas has a great effect for shortening the delay. Granting that, owing to the residual gas from the previous cycle, a higher gas-temperature before the ignition may bring this difference, it is interesting that raising the wall temperature shortens the delay with the two-stroke operation at higher rate than with the four-stroke operation.

On duration of combustion

The engine performance is largely affected by the later stages of combustion or the after-burning period. Hereupon, primary attention is paid to the fact that the duration of combustion is long with the two extreme directions of fuel injection, namely with the 0-and the 80-deg. directions.

With the 0 deg. direction, only a smaller amount of the injected fuel is able to reach the wall, but there is apt to be generated a fuel-rich mixture in the central part of the combustion chamber where the air velocity is relatively low⁽¹⁾. The combustion takes place in deficiency of air, and the unburned fuel comes to be exposed to the hot gas produced suddenly through the early explosive reaction, thus resulting in thermal cracking finally to lead to soot formation. For this reason, a longer duration is accompanied with a brighter flame. A. Pischinger, F. Pischinger have drawn illustrative examples from their bomb tests, about which they have stated that a longer ignition delay brings a shorter combustion period with a tendency to cause knocking, and that a shorter ignition delay causes a poor mixture which assists the thermal decomposition of itself⁽²⁾. With the 0 deg. direction, for which a likely explanation can be made, the duration of combustion becomes longer as the delay is shortened by the temperature

rise in the wall.

In the 80 deg. direction, it has been observed that the flame is dragged toward the center of the chamber with its end adhering to the wall, in the later stages of combustion. Fig. 9 shows a schematic view of this, where the curvature of the wall and the air stream is entirely neglected. Through the heat transfer from both the wall and the flame, the fuel adhering to the wall is gasified, and the vaporized fuel forms a flame front bordering on the fresh air stream, while the actual flame appears spread because of turbulence in the stream. According to this interpretation, it seems probable that the air velocity of the peripheral stream of the swirl and the distribution of the liquid fuel-film spread upon the wall are most important for the burning velocity. In the swirl field weakened in the later stages of combustion, the flame lasts for a longer period, but, the wall temperature being low compared to the flame temperature, the fuel is prevented from thorough cracking.

In considering these two extreme cases, it has been shown that both the incomplete combustion due to local deficiency of oxygen and the adhesion of the fuel to the wall in liquid phase are the most important governing factors for the duration of combustion. In the interim directions, combustion is protected from these influences successfully, materializing a shorter duration of combustion. In addition to these, the duration is also influenced by the outflow action, of the combustibles into the main chamber, which has been proved to govern engine performance largely⁽¹⁾. According to these conceptions, the following elucidations are possible:

(1) In the 0 deg. direction of fuel injection, the duration of combustion is largely influenced by the wall temperature, as seen from Fig. 6, because shortening the delay causes a poor mixture. On the contrary, in the 80 deg. direction, the wall temperature has a relatively small effect upon the duration in spite of a large effect on the ignition delay, because the fuel absorbs heat for evaporation, not from the wall but mainly from the flame in the later combustion stages.

(2) There exists a wall temperature to attain minimum duration of combustion, in the cases of

Fig. 9 Sketch of later flame stages of the 80 deg. direction of fuel injection

15- and 45 deg. directions. In the lower temperature range the duration increases with the lowering wall temperature because the influence of the fuel adhering to the wall is predominant, and, in the higher temperature range, the duration increases with the wall temperature because the effect of the thermal decomposition is predominant.

(3) As seen from Fig. 7, the maximum rate of pressure rise is largely affected by the direction of fuel injection. This is because the fuel quantity, which concerns the explosive autoignition, decreases as the direction of injection approaches the wall, the remainder staying at the wall.

5. Some phenomena occurring in the M-combustion system

With the 80 deg. direction, the combustible mixture formation is so restrained by the wall that the maximum rate of pressure rise is very low, showing a distinctive character of so-called M-combustion system⁽³⁾. The nature of this combustion system can be revealed to some extent by inquiring into the combustion system in the 80 deg. direction, although the situation is somewhat different from that of the actual M-engine. Some characteristic phenomena observed will be presented here for this purpose.

Relation between the wall temperature and the maximum rate of pressure rise The maximum rate of pressure rise increases slightly with the wall temperature, as seen from Fig. 7, and this inclination is inverse to those at 0- and 15 deg. directions. This shows that the evaporation of fuel from the wall is prolonged when a lower wall temperature. As the wall temperature increases, the ignition delay is shortened but the rate of evaporation increases, so that the maximum rate of pressure rise and the peak pressure are raised with the increasing wall temperature. As mentioned in the description of the indicator diagrams, the pressure rise is slow at first but accelerated later when the wall is at a lower temperature, because the fuel is heated through the flame to be evaporated with an increasing rate by degrees.

Blue flame combustion Under an adequate condition in the wall temperature and the fuel amount, a blue flame can survive for a relatively long period. An example of such a flame is given in Fig. 10 (A), showing that the first three frames are of the blue flame and that the ordinary yellow flame begins at about 17 degrees after TDC, although the only ascertainment was by the naked eye and the color film could not serve it. It is clear from the corresponding indicator diagram that the pressure attains a peak through the blue flame combustion.

However, such a combustion becomes shorter or disappears with slight changes in the wall temperature or the fuel quantity, so that it seems difficult to realize a perfect evaporate-combustion throughout the whole stages of combustion in the M-system.

Ignition from several positions Fig. 10 (B) shows a flame photograph of the ignition occurring simultaneously from several positions and its subsequent spread of combustion, which was taken with a relatively large amount of fuel injected. Because the flame spreads over from such several points near the wall, pressure rises more rapidly than else, and the flame is still vortical with its end fixed upon the wall. In the later stages of combustion, the form becomes similar to what has been mentioned previously, and the combustion is completed within a relatively short duration notwithstanding the larger amount of injected fuel.

Abnormal shortening of ignition delay Fig. 11 (a) shows indicator diagrams for different wall temperatures in the two-stroke operation. When the

wall temperature is at 350 deg. C, the pressure begins to rise above the compression line before injection, and the fuel introduced in the stroke ignites so rapidly that pressure attains a considerably high peak-pressure. It is obvious that the residue of the fuel in the chamber promotes the ignition, as observed in the flame photograph of Fig. 11 (b), in which there exists a faint blue flame at about 20 deg. before TDC. However, such a phenomenon cannot be found with the four-stroke operation.

6. Conclusions

The influences of both the direction of the fuel injection and the wall temperature were investigated and the following results were derived:

(1) Ignition of fuel is delayed by the cooling effect of the wall when the wall temperature is low, and this trend grows more remarkable as the direction of injection gets nearer to the wall.

(2) Duration of combustion is prolonged by increasing the concentration of fuel particles in the middle part of the combustion chamber and by

(A) Blue flame combustion
(B) Ignition from several positions
Fig. 10 Flame photographs and indicator diagrams

(a) Indicator diagrams for different wall temperatures
(b) Flame photographs of abnormally shortened ignition-delay

Fig. 11 Indicator diagrams and flame photograph of the 80 deg. direction in two-stroke operation

shortening the ignition delay as well as by the increase of the fuel adhering to the wall, which mitigates the rate of pressure rise due to combustion.

(3) When the fuel is injected along the wall, several features of combustion were observed, namely, the blue flame combustion, the ignition from multiple positions and the abnormal shortening

of the ignition delay.

References

- (1) F. Nagao u. H. Kakimoto: *MTZ*, Jg. 20, Nr. 6 (1959), S. 183; Nr. 8, (1959), S.303.
- (2) A. Pischinger u. F. Pischinger: *MTZ*, Jg. 20, Nr. 1 (1959), S. 5.
- (3) J. Meurer: *SAE Trans.*, Vol. 64 (1956), p. 251.
- (4) J. Alcock and R. Watts: *CIMAC-A7* (1959), p.246.

Discussion

K. Saji: (1) Show some measured outputs, fuel consumptions and exhaust gas temperatures, if any, for every direction of fuel injection presented in the paper.

(2) How does the "outflow action of the fuel into the main combustion chamber" work in a practical engine, to which authors have referred as one of the governing factors for the duration of combustion in the swirl chamber?

(3) In the cases of lower and higher wall temperature at the 0 deg. direction, authors' explanation that considerable discrepancy in the peak pressure has been originated from the mixture formation in the delay period, seems incomprehensible because of such a tiny difference of the ignition delay as 2 degrees in crank angle, notwithstanding the fact that the ignition starts about 10 deg. after injection, as seen from the indicator diagrams.

(4) The peak pressures shown in the figures seem exceedingly low for the running with load, compared with the ordinary values (c.f. Benz, *ATZ*, Heft. 6 (1959), or after the discussor's experience).

T. Kuroiwa: (5) Have authors confirmed the completeness of combustion in the case of fuel injection along the wall, while Pischinger has confirmed it when the wall is sufficiently hot (at 320 deg. C)? Some amount of the fuel seems to be left over to the following cycle, as seen in the indicator diagrams of Fig. 11.

(6) What do authors think about the fact that the minimum temperature to fire for two-stroke operation is lower than that for four-stroke operation? There seems to exist a portion of unburned fuel left till next compression stroke, which helps the ignition of the injected fuel in the following cycle through an action of pre-flame reaction. By this action, ignition delay at a steady running may also be shortened to considerable extent.

(7) The inquirer has a doubt about whether the flame photograph of Fig. 10 (A) corresponds exactly to its indicator diagram, in which the pressure rise after TDC seems to be too large for a blue flame combustion, and in which no evidence can be pointed out in the early stages of the

yellow flame combustion.

(8) It would be useful if the results of fuel injection more tangential to the wall surface could be presented.

K. Miyajima: (9) Throughout the testing, the engine speed is fixed nearly constant at 1250 r.p.m. or 1500 r.p.m. The discussor wonders if the authors have even tested under various speeds, especially at higher r.p.m.

(10) I think that the measuring point of the wall temperature is improper in the case of the injecting direction 45 deg., because this point is just injected and adhered by fuel, isn't it? For data collection, did the authors catch the first chance of ignition.

(11) The authors state that "when the fuel is sprayed onto the wall, no cracking takes place because the wall temperature is lower than those of air and flame." But the discussor consider that the cracking takes place when the wall temperature was raised to about 320 deg. C, because it is said that no blue-flame combustion is observed and the flame becomes bright.

(12) Again concerning (10), though the temperature fluctuation at the measuring point of the wall temperature may be slight against the time, it is considered that that of the very wall-surface temperature is considerable. Was there any difference observed in the state and time-interval from the beginning of the fuel injection till the equilibrium depending on the directions of injection?

Author's closure

(1) The authors are sorry not to have presented the results of performance test, because the test engine was solely constructed for the visualisation of the combustion process and incompetent for the test as such.

(2) If the fuel is prevented to flow out from the swirl chamber into the main chamber, the air will become deficient for the fuel in the swirl chamber, in the full load condition or near it, resulting in a longer and imperfect combustion. Directions of the fuel injection to remove it and to

promote the flowing-out have been made known in Ref. (1).

(3) What occurs in the delay period before ignition was inclusively explained as the mixture formation, because the pre-reaction in this period is so complicated by nature. The mechanism of the reaction might be varied by the ambient air temperature in the combustion chamber. If the fuel is distributed at the center of the chamber, in which the fuel is concentrated in the middle part, some factors to develop the rapid reaction are formed at a lower temperature, while the retardation of combustion, at a higher air temperature, is apt to happen through the thermal cracking which removes the rapid pressure rise, as mentioned by J. Meurer⁽³⁾. Such a difference must have resulted in the maximum pressure and the duration of combustion, between 150 deg. C and 250 deg. C of the wall temperature.

(4) The effective compression ratio was selected to be 13.0 and the fuel was of high cetane number, so that the peak pressure might be within the allowable pressure for the glass window.

(5) It seems difficult to argue about the perfectness of the combustion only from this experiment. Fig. 11 shows merely a rare case of the two-stroke operation, in which the fuel is left over to the next firing stroke, and such a phenomenon could never be seen with a higher wall temperature in the four-stroke operation. Once the wall temperature is made to exceed over a certain limit, the cracking of the fuel will be spurred by the wall leading to the retardation of combustion. However, with the ordinary range of the temperature and the fuel quantity, the fuel may be burned almost perfectly.

(6) It is obviously because of the residual fuel or gas, as suggested by Dr. Kuroiwa, that the minimum temperature to fire is lower in the two-stroke operation than in the four-stroke operation. On this account, the fuel injection in every other revolution was adopted for the experiment. Ignition delay shown in Fig. 8 was measured under the condition that no fuel might be left over to the next firing stroke, so that the difference of the ignition delay seems to be caused not through the influence of the residual fuel but through some

thermal effects from previous cycle.

(7) The flame photograph and indicator diagram of Fig. 10 (A) do not fail to coincide with each other. The maximum rate of pressure rise, whose measured value is 0.75 kg/cm²/deg., seems not so large as in view of that occurring in the spark-ignition engine, and the similar shapes of the pressure rise are to be found in the indicator diagrams when the gasoline engine is ignited by ignition agents.^(a) It should be noted that the blue flame combustion never signifies a so-called cool flame reaction, on that occasion, but the combustion in the rare gas-phase or the chain reactions, and that the extent of the flame luminosity is no measure for the actual rate of heat release, as stated by Meurer.^(b)

(8) The possible angle of the fuel jet of this experiment was 25 deg. to the wall, because of the injection nozzle available. By the way A. Pischinger u. F. Pischinger have experimented with the angle down to 14 deg., and in the M-combustion chamber of M.A.N. it is 15 deg. measured from a figure.

(9) Influence of the engine speed is not fully investigated with the 80 deg. direction. Some results are reported in Ref.^(c) for the injection direction similar to the 15 deg. in this paper.

(10) The films and cards were sampled from the fired cycles of a few seconds after the engine was warmed up properly through motoring. The wall temperature seems changed but a little in such short duration of firing.

(11) Though partial cracking of the fuel do happen even with the injection along the wall, what authors meant is that thorough cracking does not occur which finally leads to soot formation if the fuel is in contact with the wall.

(12) A considerable deviation would be present in the surface temperature distribution of the combustion chamber wall. But, in the appearances and time in the fired running before photographing, authors found no great difference depending on the directions, except at the very beginning of the firing, as seen from indicator diagrams.

(a) F. Nagao, T. Kobayakawa, et al: *Trans. Japan Soc. Mech. Engrs.*, Vol. 23, No. 132 (1957), p. 579.

(b) J. Meurer: *Preprint for SAE Inter. Congr.* (1961).

(c) F. Nagao and H. Kakimoto: *Memoirs Fac. Engng., Kyoto Univ.*, Vol. XXII, Part 2 (1960).