Flame Propagation in Spark Ignition Engines*

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By two new electronic methods—(a) a digital method and (b) a gray wedge scope method—the propagation of the flame in the spark ignition engines was studied. Making use of the ionization gaps, the arrival of the flame front was detected, and how the flame travels in the combustion room could be made clear. These methods have the advantage that statistically enough data can be easily obtained. From the obtained shape of the time frequency distribution curve for the arrival time \( t_a \), the progress of the propagation of the flame was interpreted. In practical engines, a study on the irregularities in combustion caused by changing the setting direction of the ignition plug was carried out, and some interesting effects have been observed.

1. Introduction

In an internal combustion engine, it is important to know about combustion in cylinders whenever the engine performance is discussed. One way of doing this to observe the flame propagation. However, the combustion in the cylinder of an actual engine is more complicated that in an experimental bomb or a Bunsen burner. A slow motion camera is often used to take photographs of the combustion flame through a quartz window opened directly on the wall of cylinder head\(^{(1)(2)}\). Besides, the ionization gaps method is often used for the measurement of the flame propagation. In a spark ignition engine, the combustion flame usually propagates from the point of the spark plug, therefore this method has an advantage over any other methods in that it permits studying with ease. Consequently, many investigations were performed by many persons\(^{(3)(4)(5)}\). In 1933, K. Schnauffer reported on the combustion processes in an internal combustion engine by means of ionization gaps, in which 24 measuring ionization gaps were inserted in the combustion chamber covering the entire surface and neon lamps were used; as the lamps were lighted, the course of flame-front travel could be followed. Beside this study, in investigations with preignition\(^{(6)(7)}\), or with rumbles\(^{(8)}\), this method is widely used. In this method all the recording systems measure many points over the surface of combustion chamber at the same time and the results are recorded on the oscillograph paper. But, as the circumstances of combustion in the cylinder of internal combustion engines are changing at every cycle, it leads to a misjudgement to infer from small numbers of examples. It is preferable to discuss statistically considering the combustion as an independent phenomenon occurring at engine cycle.

Hence, the measuring method of the arrival time \( t_a \) was developed by means of these ionization gaps by the author; it defines the arrival time as the time of interval during which the flame starts from the spark plug and the flame-front arrives at an ionization gap to make it a conductor of electric current. This is wholly operated electronically, and is registered by digital systems. It enables measurement of the arrival time of the flame-front, and estimation of its statistical fluctuation around the mean value. But it takes much time for measuring and the cycles not measured are much more than those measured. Hence, another method which might be called an analog method against the preceding method which might be a digital method was contrived, in which all the engine cycles were made use of in measurement, and a distribution figure of \( t_a \) is displayed on the screen of CRT. This figure can be photographed by a camera or be directly observed by the eye.

These methods were applied to actual engines, and brought a few interesting results described as follows.

2. Principles of measurements

2.1 Ionization gap method

An ionization gap method which was introduced by K. Schnauffer is to indicate the flame propagation. If an ionization gap containing two electrodes is inserted in a combustion chamber, and an
In electrical potential imposed on these electrodes, then a current starts to flow between the electrodes at the instant that the flame reaches them. When the flame-front arrives at the point of ionization gap, the current produces a pulse voltage across the series resistor to the electrode, by which the arrival time of the flame-front is known by means of any recording equipments, for example, on an oscillograph record. Particularly in the spark ignition engines, the flame is always spreading over the entire combustion chamber from a spark plug in normal combustion, proceeding from a single ignition point. The arrival time \( t_a \) of the flame-front illustrates the state of development and the uniformity of combustion processes.

2-2 Measuring of arrival time \( t_a \) of flame-front

The combustion begins normally from the spark plug and the flame-front spreads over the chamber and reaches the ionization gaps. Therefore, the arrival time required for the flame-front to travel from the spark plug to the ionization gaps may be measured by the following electronic method with ease.

(i) Digital method To indicate the arrival time \( t_a \) of the flame-front with a digital value, the following method was employed. In Fig. 1 is shown the schematic diagram of its principle. Considering the ignition time when the current flows into the spark plug the detection of ignition pulse was obtained in terms of capacity through winding a wire of few turns over the cable to the plug. A gate circuit is opened by this triggering pulse, and is closed by the pulse produced by the ionization gaps currents. During this gating period, the output pulse train of crystal-controlled oscillator having a frequency of 10 kc is allowed to pass this gate circuit, then it is registered by a dekatron counter. Therefore, the displayed numerals represent the arrival time of flame-front in units of 0.1 m sec. The time sequence chart is illustrated in Fig. 2.

(ii) Analog method (Gray wedge method)

This is a method to utilize all the engine cycles continuously against the digital method using only a small number of cycles. The block diagram of its principle is shown in Fig. 3. The detection of the ignition and the flame-front arrival is achieved by the same method as was used in the digital one, but in this case, the waveforms as illustrated in Fig. 2 from e to i are produced by the ignition and the ionization gaps pulses, respectively.

At first, a gate waveform e is triggered by an ignition pulse, thereby triggering a linear sweep g,
and it cease to sweep and holds its final value by an ionization gaps current at the instant another linear sweep h is started. The sweeping voltage g and h are applied to the deflection plates of X-and Y-axes of CRT, while unblanking signal i is applied to Z axis, respectively. Then a bright vertical line appears on the screen of CRT at the place corresponding to the arrival time \( t_a \) of flame-front from starting point of sweeping at every combustion. Therefore, the time-scale on the X-axis where a bright line is displayed indicates the arrival time \( t_a \). But if it is seen directly, it jitters at every time, therefore its distribution is not distinct. If an optical filter of gray wedge is attached at the front of screen of CRT as shown in Fig. 4, the more frequent position of the occurrence will give the more bright line. Hence, the equi-bright points represent a distribution curve of occurrence frequency. If this pattern is photographed by the camera, a distribution of \( t_a \) is obtained with a mean value of \( t_a \) and its standard deviation at the same time. And if a long-persistent CRT is employed, the distribution curve may be fit for direct-viewing.

### 3. Experimental apparatus

(1) Ionization gaps  
The ionization gaps may be any type having two electrodes which can be let to flow electric current. The materials of the gaps are most suitable if they are hard to rust because if their surfaces are stained they may be insulated. A conventional spark plug may be used as an ionization gap. Especially, if many ionization gaps are arranged spreading over the cylinder head, special units are prepared with an average electrode diameter of 2.2.5 mm set in 3 mm holes in the cylinder head using insulating cements. Here, a miniature spark plug for model aeroplane engine with a diameter of 8/8 inches was employed to which 300 volts was supplied through a high-resistance of 1 megohms.

(2) Digital method  
In Fig. 5 is illustrated a gate circuit which is triggered by an ignition pulse and by an ionization gaps pulse.

An ignition pulse is amplified by \( V_{i1} \), thereby triggering a flip-flop circuit \( V_3 \) after a manual switch \( SW_1 \) is closed, therefore as long as the manual switch closes the circuit, the gate-tube \( V_8 \) is opened, and the pulse train appears at the plate, if a frequency of 10 kc divided from crystal-controlled 100 kc oscillator, is applied to the suppressor grid. Meanwhile, the ionization gaps pulse causes the trigger signal to transit a flip-flop circuit \( V_5 \) thereby resetting the flip-flop circuit \( V_4 \) above mentioned. After all, the result is that a pulse train having a frequency of 10 kc appears only for the duration between the ignition time and the arrival time of flame-front when a manual switch is closed. This output pulse train is applied to a dekatron counter, by which \( t_a \) is then measured with an accuracy of 0.1 m sec. The reason why the output of the frequency of oscillator was used at 10 kc is that the frequency response of the used dekatrons electronic counter was capable of up to only 20 kc. Speaking from the standpoint of accuracy, this frequency is the higher the better, but it may be enough at the present frequency of 10 kc considering from the experimental results of fluctuation of \( t_a \).

(3) Analog method (Gray wedge method)

The apparatus will be described in detail with reference to Fig. 6. It is just the same way as in the digital method that a transition of flip-flop circuit \( V_3 \) is caused by an ignition pulse and is reset by an ionization gaps pulse. No difference from the digital method is observed other than the operation not by manual triggering but by actuating repeatedly at every cycle. A rectangular wave, \( c \), having a width equal to \( t_a \) as is shown in Fig. 2 appears at the plate of \( V_{1a} \). Differentiating this waveform by RC network a positive pulse and a negative pulse are obtained, respectively. A negative rectangular wave having a width of about 10 m sec is produced by this positive pulse thereby building to start a bootstrap sweeping for X-axis signal of CRT. While by the negative pulse a transition of the second flip-flop circuit \( V_{1b} \) takes place, and is
reset at the end of pulse duration of 10 msec width, then a rectangular wave as is shown by f in Fig. 2 is obtained, which is applied to the control grid of V7, thereby cutting off the current. Thus the linear sweeping is ceased keeping the potential at the instant of an ionization gaps current starting to flow. Consequently, a trapezoidal waveform is obtained as illustrated by g in Fig. 2. Meanwhile, another linear sweeping h for Y-axis signal of CRT is started using the waveform f as shown in the same figure. Amplifying these voltages and applying to the deflection plates X, and Y of CRT, an equi-bright vertical line is displayed on the screen. If a gray wedge optical filter is placed at the front of the screen, the distribution pattern of the occurrence frequency can be seen*. If 5 ABP1 type is used as a CRT, it is difficult to see the distribution curve by direct-viewing, for this purpose a 35 mm camera may be useful to take a photograph of the distribution curve.

4. Experimental results

Some experiments were performed with these methods, in which the relation between the running conditions and the distribution of t0 was observed. In the following, the results are described.

4-1 Test engine

In the experiments, two small gasoline engines were used; a two-stroke and a four-stroke engine, respectively. Their characteristics are listed in Table 1.

4-2 Installation of ionization gaps

The combustion chamber was provided with a miniature spark plug for the model engine as an ionization gap, whose size was of 3/8 inches screw. This plug was installed in the hole especially drilled on the cylinder head. However, since its heat capacity was too poor to fit for high-powered operation or high-speed running, a preignition due to overheating was often observed to disturb the experiment. Therefore, the experiment was mostly performed at less than the rating, to prevent these troubles. It is desirable to use ionization gaps with a large heat capacity. As the engine was air-cooled type, the cooling fins obstruct installation of the ionization gaps in the combustion chamber. To overcome this difficulty, a cylinder head of special make was prepared as shown in Fig. 7 and Fig. 8, respectively, in which the situation of the ionization gaps was illustrated, and the numerals indicate

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* See the appendix.
the direct distance from the spark plug.

4.3 Results

(a) Results by digital method

4 stroke engine A relation obtained between the value of the arrival time, $t_a$, and the distance from the spark plug to the ionization gaps is shown in Fig. 9, in which the relation between the two seems to be nearly linear except at a few points. The flame-front cannot always arrive earlier at the nearer point from the spark plug than at the farther point. Plotting the distribution curve around the mean value of $t_a$ to evaluate its fluctuation, Fig. 10 is obtained. This distribution curve looks similar in shape to the one obtained at an arbitrary point. Applying a procedure of certification to this distribution curve, it was proved that the classification of the distribution was a normal distribution with the following constants,

- Mean value $\bar{t}_a = 8.38$ m sec
- Standard deviation $\sigma = 0.84$ m sec

where the total number of samples was 611. The dotted line in Fig. 10 indicates the theoretical normal distribution curve, which well agrees with the experimental results. In Fig. 9, the standard deviation $\sigma$ becomes gradually larger as the spark plug and the ionization gaps become farther apart. Noting the fact that the arrival time, $t_a$, at each point is not proportional to the distance from the spark plug, it can be supposed that the presence of the earth-electrode of the spark plug may affect the initial propagation of the combustion flame. To examine this assumption, a test was carried out in two different ways, in which the earth-electrode of the spark plug was set in the direction different by 180 degrees, from each other. Under these conditions and the same running condition, the distribution of $t_a$ was measured, and the results are illustrated in Fig. 11, in which they are plotted in solid or dotted lines, respectively. It has to be noted that the difference between both cases is apparently seen.
2 stroke engine In the same way, as in the test of 4 stroke engine, alternating the setting of the direction of the earth electrode of the spark plug, the measurement was performed. The results essentially are similar to those obtained in the previous test, as shown in Fig. 12. The discrepancy in the value of $t_a$ found in these two cases amounts to the magnitude of 0.6~1.0 milliseconds, which corresponds to a shifting of about 7~12 degrees of crank-angle, at 1500 r.p.m. of engine speed. This fact may influence seriously upon the mechanism of the scavenging. The arrival time, $t_a$, at the point of A is indicated to be less than that of the point C in spite of equal distance from the spark plug, which is interpreted to be due to the presence of a scavenging flow in the combustion chamber observed in the study on scavenging with the same engine by Ohigashi\(^9\). After the experiment, inspecting the inner side of the cylinder head, the deposits suggesting a presence of the rotating flow of the scavenging like a swirl could be seen.

(b) Results by analog method

By the digital method above described, data excellent in statistics and quantity can be obtained, but it takes much time and is troublesome to execute, namely needs about twenty minutes for five hundred measurements. Hence, a measurement by the analog method on the same engine as used in the digital method was made. In Fig. 13 are illustrated the photographs obtained on the screen of CRT. The measuring conditions were as follows; the engine speed was 1500 r.p.m. and the time required for an exposure was two minutes, respectively. Therefore, the sampled data amounted to as many as about three thousand, which are statistically enough and more than obtained in the case of the digital method in a short time. In the photograph illustrated in Fig. 13 the abscissa means the arrival time, of the flame front, $t_a$, and the ordinate the occurrence frequency. It is a matter of course that the photographs show the similar figures obtained by means of the digital method as shown in Fig. 12. Figure (a) corresponds to the case represented by a solid line in Fig. 12, and figure (b) by a dotted line, respectively.

5. Conclusion

From the experiments it is significant to note that the circumstances of combustion in a cylinder can be predicted in some degree through measuring of the value of $t_a$ and its distribution curve, while it is improper to carry on an argument about the engine performance because of limited amount of data. For that, many patterns observed under many and various conditions would have to be prepared. However, it is difficult to decide which method is superior, for both methods have each their own merits as follows.

(i) According to the digital method, the value of $t_a$ can
be quantitatively and statistically obtained. Therefore, the distribution of $t_a$ can be obtained precisely under certain operational condition and the standard patterns can be prepared.

(ii) According to the analog method, the distribution of $t_a$ can be seen directly on the screen of CRT especially with use of a long-persistent CRT. Thus, the circumstances of combustion in a cylinder can be predicted immediately with the aid of distribution patterns thus obtained.

Combination of the digital method with the analog method will provide a complete means for improving the engine performance. However there is the drawback that these methods can apply only to the spark ignition engines; it will be a future subject of study to make them applicable to the Diesel engines.

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Appendix

(a) Principle of gray wedge filter

Assuming that the intensity of a spot, $I_o$, on the screen of CRT becomes $I_1$ after traversing through an optical gray filter whose thickness is defined as $d=f(y)$ and its absorption coefficient is $\alpha$ as shown in Fig. 14, the following equation can be obtained

$$I_1 = I_0 e^{-\alpha d} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \qa
\[ I_1 = I_0 e^{-\alpha y} \]  \hspace{1cm} (2) \\
\[ \log \left( \frac{I_1}{I_0} \right) = -\alpha f(y) \]  \hspace{1cm} (3) \\
(b) In the case of photographing the trace on the screen of CRT 

Instead of direct-viewing of the trace on the screen of CRT, if they are photographed by the camera, all the illumination arriving at the photographic emulsions will be integrated by them under certain conditions as long as the following relation is substantiated, and is denoted the total light intensity integrated during the exposure is denoted by \( I_b \)

\[ I_b = k I_1 = k I_0 e^{-\alpha f(y)} \]  \hspace{1cm} (4)

where \( k \) is the number of repetitions of the light pulses. Denoting the total light intensity of \( m \) and \( n \) of pulses by \( I_m \) and by \( I_n \), respectively, referring Eq. (3) one obtains

\[ m I_0 e^{-\alpha f(y_m)} = n I_0 e^{-\alpha f(y_n)} \]  \hspace{1cm} (5)

in which \( y_m \) or \( y_n \) represents the pulse height on the screen of CRT, at which the brightnesses of the traces are equal to each other. Thus.

\[ n e^{-\alpha f(y_n)} = m e^{-\alpha f(y_m)} \]  \hspace{1cm} (6)

\[ \log \left( \frac{m}{n} \right) = f(y_n) - f(y_m) \]  \hspace{1cm} (7)

Now, if a linearly tapered wedge is employed, one obtains

\[ f(y) = cy \]  \hspace{1cm} (c: a constant) \hspace{1cm} (8)

then, Eq. (7) leads to

\[ \log \left( \frac{m}{n} \right) = c(y_n - y_m) \]  \hspace{1cm} (9)

Therefore, the displacement along the wedge is proportional to the logarithmic value of the number of sweepings. It is desirable to use a gray wedge having actually a shape of wedge; however, a wedge which is optically a gray wedge can be made from a photographic emulsion. Generally, in the photographic emulsion, there is a region which satisfies the following relation between the exposure \( E \) and the density of blackening of the emulsion, \( D \) (a region of moderate exposure)

\[ D = \gamma \log E \]  \hspace{1cm} (10)

where \( \gamma \) is the contrast of the emulsion. Further, \( D \) is defined as

\[ D = \log \frac{I_0}{I_1} \]  \hspace{1cm} (11)

From Eqs. (9) and (10), the light intensity through the emulsion with a contrast of \( \gamma \) is given by

\[ I_1 = I_0 E^{-\gamma} \]  \hspace{1cm} (12)

Now, if the emulsions are exposed to a light whose intensity distribution is expressed by \( E(y) = p y I_0^* \) \( (I_0^* \text{ light intensity}, p: \text{a constant}) \), the distribution of the blackening density is given by

\[ f(y) = \gamma \log (p y I_0^*) \]  \hspace{1cm} (13)

Hence, the distribution of light intensity through this developed emulsion is represented by the following equation, referring to Eq. (1)

\[ I_1 = I_0 (p y I_0^*)^{-\gamma} \]  \hspace{1cm} (14)

Every emulsion has its own value of \( \gamma \), which usually fluctuates around the value of about 0.7 to 1.5; therefore, it is impossible to realize \( \gamma = 1.0 \) by controlling the developing process by some suitable treatment, and to arrange that the distance along the wedge may be proportional to the number of sweepings.

(c) In the case of direct-viewing with a long-persistent CRT

In the case of using a general purpose CRT, for instance, 5 ABP 1 tube, the persistent time of luminescence of the screen is short, therefore, it is difficult to recognize the distribution of the traces on the screen of CRT by the eye. However, using a long-persistent time of luminescence such as 5 ABP 7, the distribution curve may be observed as a yellow persistent trace provided that a yellow optical filter is mounted on the CRT face. In practice, the old traces are fading gradually with a persistent time constant, then if the brightness of the spot at the most frequent point of \( I_t \) is adjusted to the saturated brightness of the luminescence of the CRT, the other point of equi-brightness will fall on a curve of the distribution of \( I_b \), with a narrower width than that of actual distribution. It is rather convenient to find a mean value of \( I_t \).

References

(9) S. Ohigashi and M. Kita: In press.

*A dry-plate is exposed to the light with a mask moving at a constant speed along y-axis.*