Flame Development and Combustion Pressure in the Gasoline Injection Engine

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Introduction

As is well known, the flame propagation in a spark ignition engine is the chief factor which controls the rate of pressure rise and hence, it has an important influence on engine performance. Recently, studies have been made of flame development in engines equipped with carburetors by photographing the flame through the transparent windows of various kinds in the cylinder head.1) From these test results, the relation between flame development and pressure rise was clarified. However, in a gasoline injection engine, it is expected that the distribution of fuel is not uniform at the moment of ignition and the combustion properties are different from those in a carburetor engine, as was pointed out in the foregoing paper.2)

The object of the experiments described in this paper is to investigate the rate of flame propagation and the combustion pressure in the gasoline injection engine and to compare them with that in the carburetor engine.

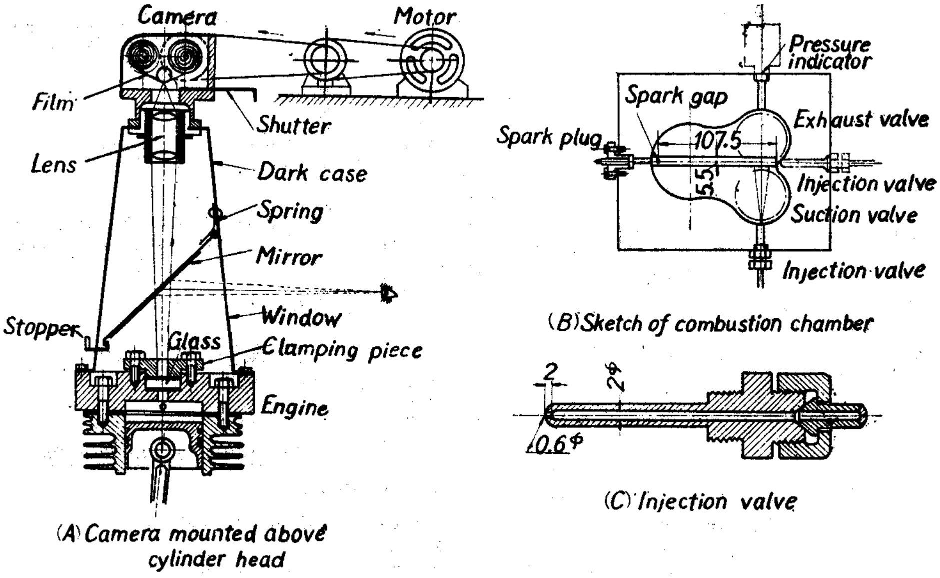
I. Flame Propagation and Combustion Pressure in the Cylinder

A. Test Apparatus

Fig. 1 shows the test apparatus.

(a) Test engine. An autocycle gasoline engine (air cooling, single cylinder, four stroke, having L type combustion chamber, 71 mm bore, 91 mm stroke, and compression ratio of 4.3 : 1) was used, adding the fuel injection system to drive it with cylinder injection.

It is equipped with a special cylinder head having a narrow window extending from one end of the combustion chamber to the other as shown in the diagram. The window pane is of terex glass, so that the flame movement in the combustion chamber can be observed through it. The center electrode of the spark plug is



(A) Camera mounted above cylinder head

(B) Sketch of combustion chamber

(C) Injection valve

Fig. 1. Cylinder head and photographing apparatus of flame

extended into the combustion chamber so that the spark discharge can be observed through the window. A battery ignition system is used. The injector is of an open nozzle type specially designed for this experiment, and the fuel is sprayed from the side of suction valve towards the exhaust valve. The fuel injection pump is of a Bosch type for Diesel engine use, the diameter of its plunger being 8 mm.

(b) Recording apparatus. The camera is attached at the upper end of the dark case mounted on the engine cylinder to photograph the flame movement. The lens has a focal distance of 2 inches and a diaphragm number (f) of 2. Photographs were taken on 35 mm X-ray films, with a feeding speed of 0.8 m/s.

The camera is so mounted that the film motion is at right angles with the window. Therefore, when the film is run through during the engine operation, the locus of flame front is photographed as shown in Fig. 2.

In order to mark the spark time and TDC on the picture, induction coils are used, the primary circuits of which are interrupted at each period. Thus, owing to high voltage induced in the secondary coils, the spark discharges occur at the spark gap in the camera, and they are recorded on the film. The secondary circuits of these induction coils are terminated at a spark gap, which in consequence gives discharges separately at each period. For the recording of standard time, an induction coil is also utilized, and the spark discharge of constant frequency is applied by a standard electro-magnetic tuning fork, the natural frequency of which is 100 cycles per second. The circuits for these recordings are illustrated in Fig. 2.

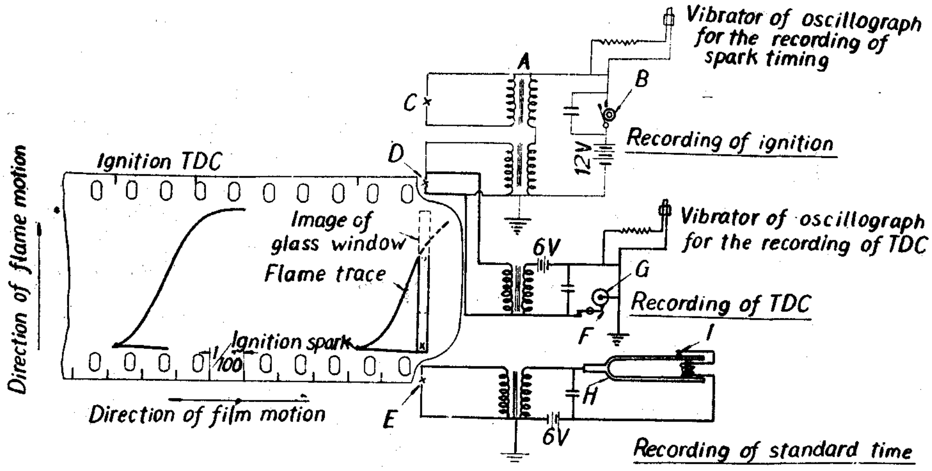


Fig. 2. Method of recording

A: Ignition coil
B: Interrupter
C, D, E: Spark gap
F: Breaker-contact for TDC
G: Crankshaft of the engine
H: Tuning-fork
I: Interrupting contact

A photo-electric cell indicator is used for measuring the combustion pressure, connecting it with an electro-magnetic oscillograph.

An electric gas analyser is used for measuring the mixture ratio, taking the exhaust gas from the exhaust pipe. It is corrected by comparing its readings with the results obtained from an Orsat's gas analyser.

(c) Test method. The engine is driven with the following four kinds of fuel and is loaded by a D.C. generator, directly coupled with it.

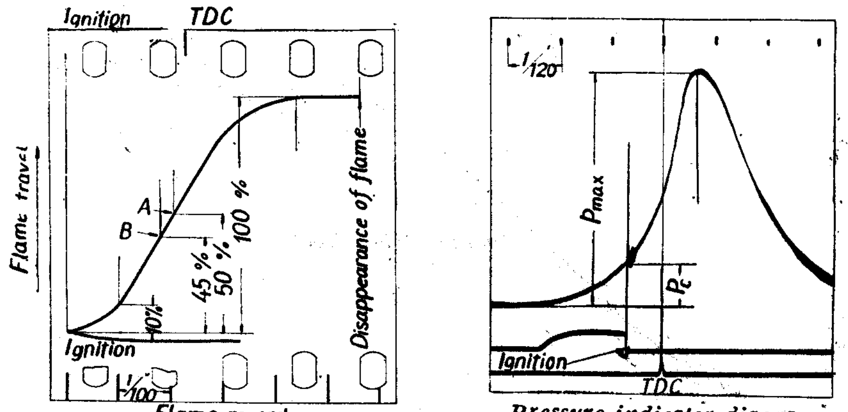
Notation	Kind of fuel	Specific gravity	Octane number
A	No. 13 Secondary reference fuel	0.71	94
B	No. 12 Secondary reference fuel	0.73	71
C	No. 11 Secondary reference fuel	0.74	49
D	Commercial gasoline	0.73	71

At first, the flame propagation in the injection system was compared with that when running under carburetor system. In the next place, the effects of injection timing and spark advance on flame propagation were investigated, when the engine was driven by the injection system.

B. Test Results

(a) Explanation of flame photograph and indicator card.

The explanation of the record is illustrated in Fig. 3. On the record of flame trace, the two marks at the upper side of the film indicate the ignition timing and



Flame record *Pressure indicator diagram*

Fig. 3. Explanation of the records
p_c=compression pressure p_{max}=maximum pressure

TDC, and at the lower side, the standard time marks are recorded. The curve of flame trace can be divided roughly into three parts, that is, the first period of gradually increasing flame velocity, the period of constant flame speed, and lastly the period of decreasing flame velocity when it approaches the end of the flame travel. Further, after-glow continues for some time after the flame completes its travel. The four periods above mentioned can not be defined exactly, therefore the following definitions are adopted. The time occupied for the first 10% of flame travel is considered as the first period.[3] In the same manner, the time occupied for 50% and 100% of flame travel are decided.

The velocity of flame propagation is determined by the slope of the flame locus in the middle period of constant gradient, that is, the inclination of the straight line AB in Fig. 3, where A and B are the points of 50% and 45% travels on the flame trace. In addition, the mean flame velocity is decided, which is obtained by dividing the total travelling distance by the time interval while the flame front crosses it.

The shape of the flame trace is not the same for each cycle even when the engine is running under the same conditions. As an example, the flame fronts under the same running conditions are superimposed in Fig. 4. The average flame front for each run is determined from 6 to 9 flame photographs, as shown in the figure. Therefore, the data shown in this paper illustrates the mean value.

The image of the window on the film has a breadth of 1.1 mm in the direction of the film motion, so the velocity of flame propagation obtained here is not exact. The present method, however, will serve the purpose of this study, because it indicates the trends in the average velocity of the flame front when some running conditions are changed.

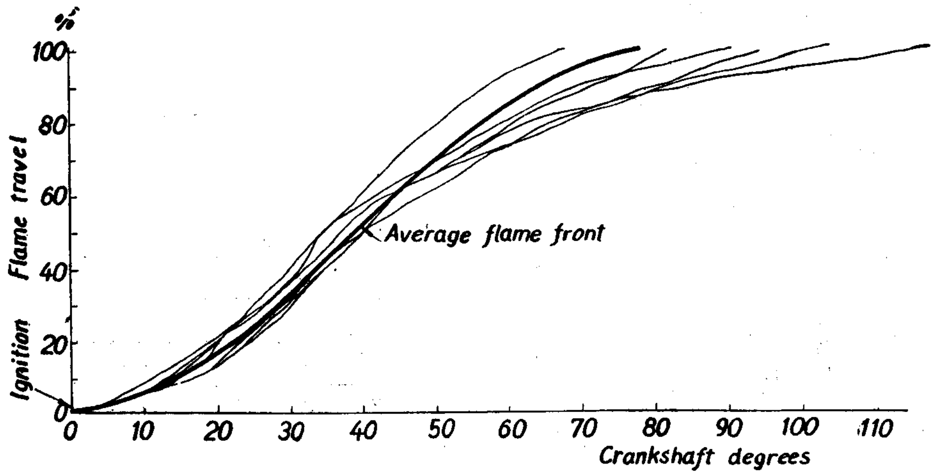


Fig. 4. Superimposed flame front

The indicator card is shown in Fig. 3. The pressure curve oscillates at the moment of spark discharge, which is caused by the electrical disturbance of spark felt on the amplifier, and it has no relation to the pressure change.

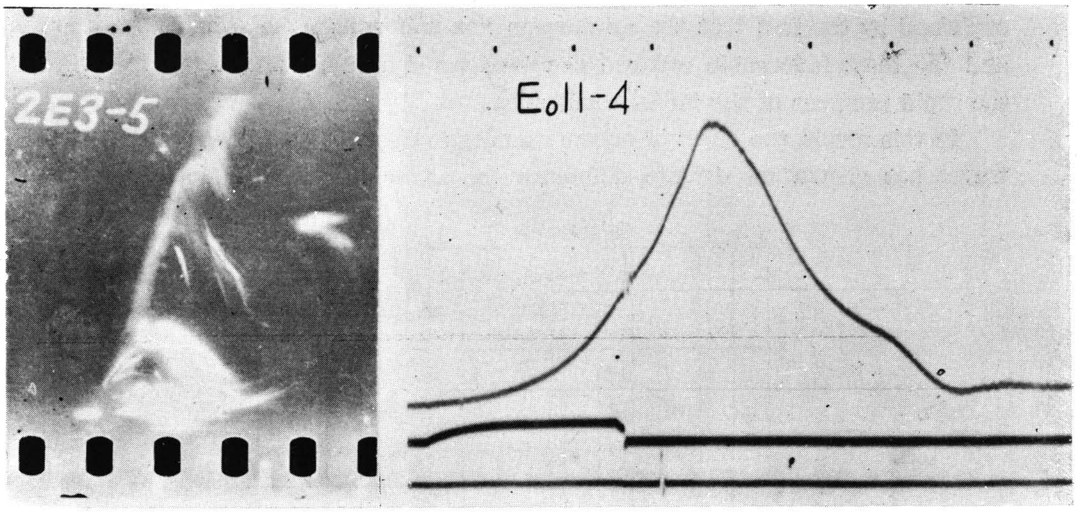
(b) Comparison of combustion properties for both fuel systems.

In a gasoline engine, the combustion properties are affected the most by mixture ratio. The differences in the combustion properties between the carburetor and injection system are investigated for various mixture ratios. Moreover, using the three kinds of fuel having different octane numbers, its effect on combustion was determined.

Comparison of the flame picture. Fig. 5 shows the typical records of flame for both types as well as indicator diagrams. With carburetor, the period of the glow after passage of the flame front is short, while in the injection system, it is extremely long. This difference occurs because, with carburetor, the fuel is well mixed and the reaction is completed almost at the flame front, on the contrary, with cylinder injection, the reaction continues for some time after the arrival of the flame front as discussed in the foregoing paper.2) Fig. 6 and 7 show the test results.

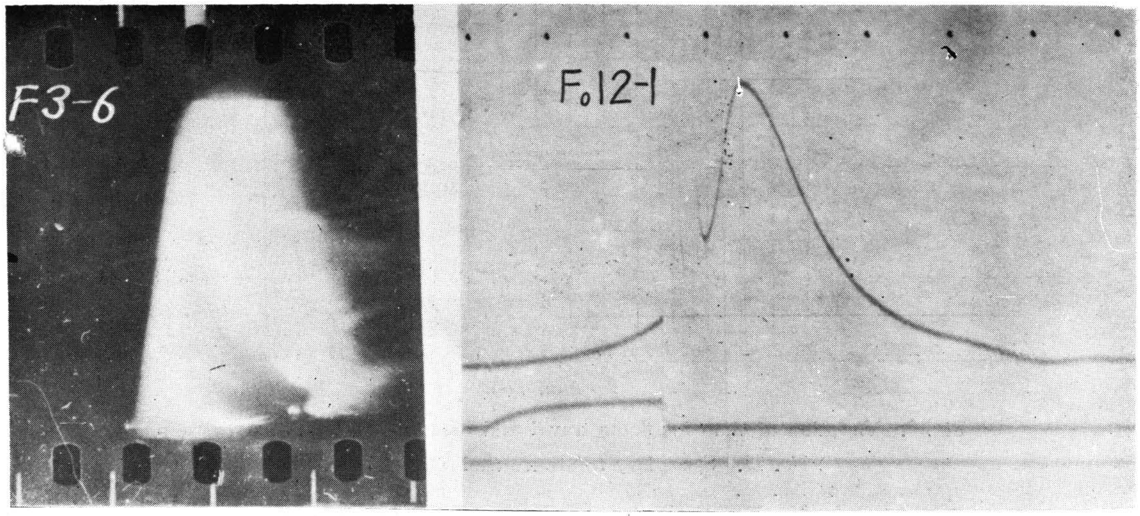
Flame propagation. The time for flame travel is minimum at the air-fuel ratio of about 11 : 1 for both fuel systems. However, it is smaller with injector than with carburetor.

The remarkable difference between the two types is the ignitable range of mixture ratio. It is reduced in the cylinder injection as compared to carburetion, owing to the imperfect mixing of fuel and air. From these results, the control of charging quantity in the injection system is important to obtain an ignitable mixture at the spark gap. The reduction of the travelling time of the flame in



Flame picture Indicator diagram

Carburetor system



Flame picture Indicator diagram

Injection system

Fig. 5. Typical example of flame pictures and indicator diagrams

the fuel injection is due to the shortening of 10% travelling time, that is, the rapidity of the flame development immediately after ignition. This result may be explained by the fact that the mixture is non-uniform in the cylinder injection and the most favourable mixture can be formed near the spark gap, following the rapid progress of the initial combustion.

In this result, the effect of octane number is clear. The time interval of 10% travel has shown no definite difference in octane numbers of fuels. In the

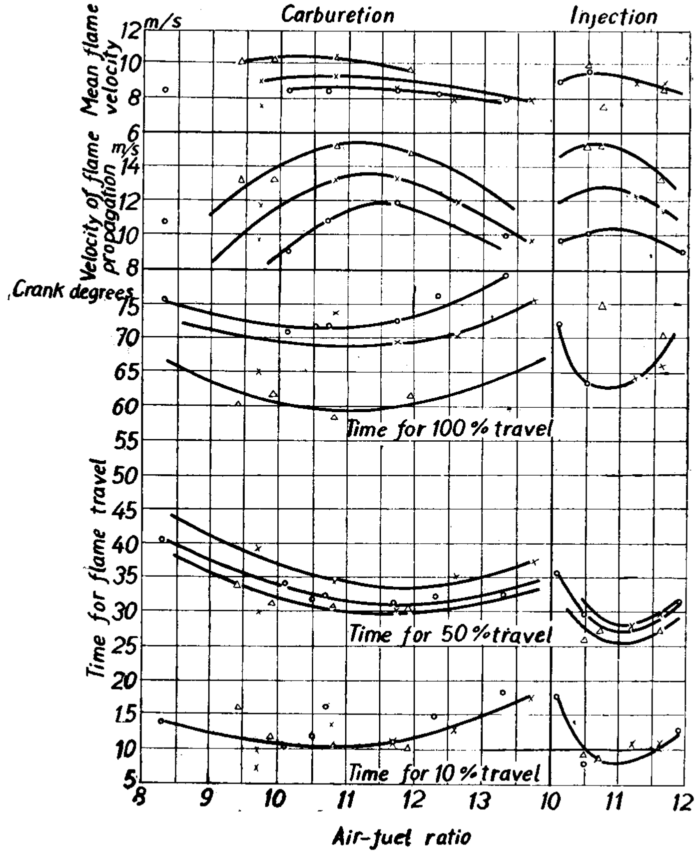


Fig. 6. Variation of time for flame travel and flame speed with mixture ratio

○ No. 13. Secondary reference fuel (Octane No. 94)
× No. 12. Ditto (Octane No. 71)
△ No. 11. Ditto (Octane No. 49)

	Carburetor system	Injection system
Engine speed	1000±91 rpm	1000±91 rpm
Output	0.63 HP	0.65 HP
Throttle	1/8	1/5
Ignition timing	38±5° before TDC	25±2° befor TDC
Injection timing		14° after TDC on the suction stroke

carburetor system, however, as the travelling distance of the flame increases, its effect becomes clear and the time interval of 100% travel is longer for the fuel having higher octane number. This fact means that the rate of combustion in the end mixture increases with the decrease of octane number. On the contrary, no distinction caused by the difference of octane numbers can be seen in the cylinder injection.

The time interval between ignition and maximum pressure is somewhat shortened in cylinder injection. At the same mixture ratio, it increases with the increase of octane number. These results are in agreement with those of the flame movement described above.

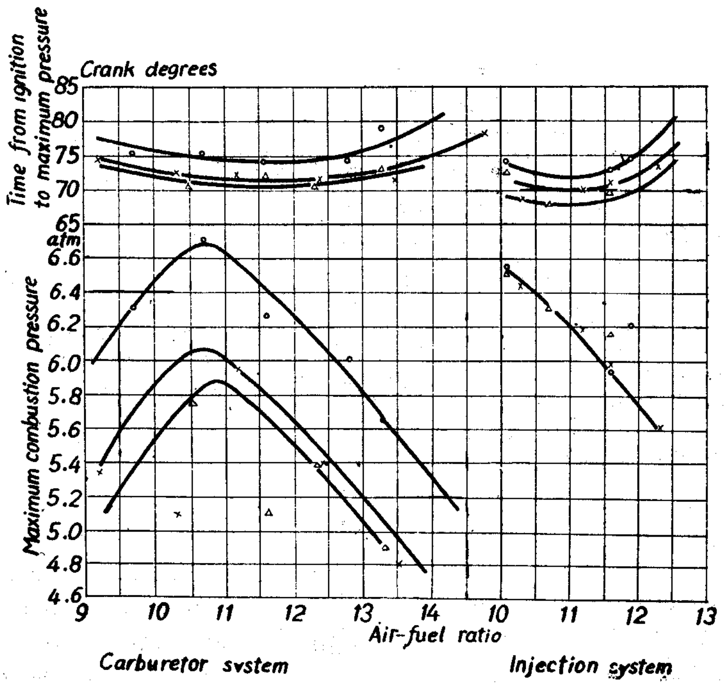


Fig. 7. Variation of maximum pressure and time from ignition to maximum pressure with mixture ratio

○ No. 13 Secondary reference fuel (Octane No. 94)
× No. 12 Ditto (Octane No. 71)
△ No .11 Ditto (Octane No. 49)

	Carburetor system	Injection system
Engine speed	1000±29 rpm	1000±62 rpm
Output	0.63 HP	0.63HP
Throttle	1/8	1/5
Ignition timing	24±3° before TDC	25±2° before TDC
Injection timing		14° after TDC on the suction stroke

The velocity of flame propagation is maximum at the air-fuel ratio of about 11 : 1 for both fuel systems. At the same mixture ratio, it decreases with the increase of octane number. The general tendency of the mean flame velocity is similar to the velocity of flame propagation.

Maximum combustion pressure. It attains the maximum at the mixture ratio somewhat richer than 11 : 1 in the carburetor system. With injection system, however, it increases with the increase of the charging quantity, and there is no tendency to decrease even at an air-fuel ratio of 10 : 1. This is the most remarkable difference between the two types. Further, with carburetor, the maximum combustion pressure increases as the octane number increases, whereas with cylinder injection no such a trend is observed.

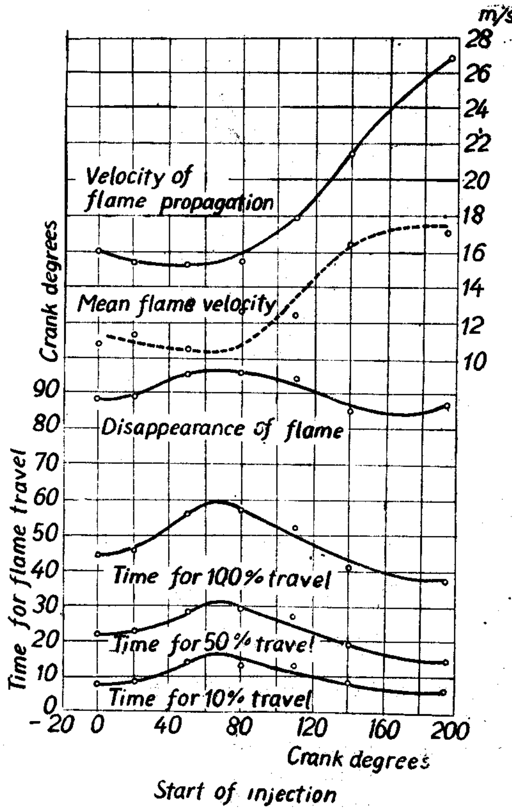


Fig. 8. Variation of time for flame travel and flame velocity with start of injection

Engine speed: 1000±62 rpm
Output · 0.63~0.82 HP
Throttle: 1/4
Air-fuel ratio: (10.4±0.5) : 1
Ignition timing: 39±4° before TDC

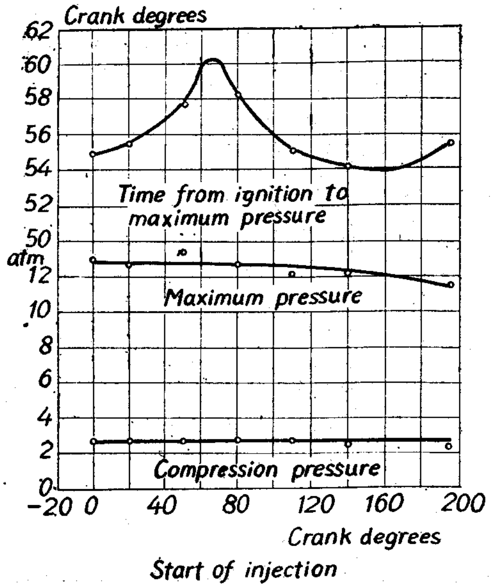


Fig. 9. Variation of maximum pressure and time from ignition to maximum pressure with start of injection

Engine speed: 1000±62 rpm
Output : 0.41~0.6 HP
Throttle: 1/4
Air-fuel ratio: (11±1.4) : 1
Ignition timing: 36±2° before TDC

(c) Effect of injection time.

When the start of injection is changed, the time interval allowed for the vaporization varies, therefore the concentration of fuel vapour and its distribution in the mixture at the moment of spark should be changed. The results for various injection time are shown in Fig. 8 and 9. These results show the effect of mixing the fuel and air, because only the injection time is changed and the other conditions are kept constant.

Flame propagation. The time required for flame travel increases at first with the delaying of injection start from TDC to 60 degrees, but for later injection, it decreases. With later injection than BDC, however, the ignition becomes unreliable and the engine misfires frequently and the normal operation can not be carried out, resulting in the late disappearance of flame.

The time from ignition to the maximum combustion pressure shows the same tendency as the time from ignition to the disappearance of flame. The maximum combustion pressure appears slightly after the flame front completes its total travel and the combustion glow continues for 30~40 crankshaft degrees after the maximum pressure is attained.

With the injection later than 60 degrees after TDC, non-uniform mixture may be formed, which gives a relatively good performance for initial combustion progress, resulting in the rapid flame travel. With very late injection, however, the progress of vaporization is imperfect at the moment of ignition and the time required for combustion increases. In some cases, the inflammable mixture can not be formed at the spark gap and the engine misfires. The fuel, which has not vaporized before the flame front reaches it, burns after the flame front has passed through, hence the increase of combustion interval results.

A delaying of injection start from TDC decreases the velocity of flame propagation slightly until the start of injection of 60 degrees after TDC, but with further delaying it increases rapidly.

Maximum combustion pressure. The maximum combustion pressure decreases as the start of injection is delayed. The compression pressure*, however, is almost constant, therefore the pressure rise due to combustion decreases with the delaying of the injection.

(d) Effect of ignition advance in the injection system.

The flame propagation and combustion pressure were investigated for various spark advances, keeping the start of injection at 35 degrees after TDC. Fig. 10 and 11 show the results.

Flame propagation. The time interval required for 100% travel decreases

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* The compression pressure means the pressure at the moment of ignition.

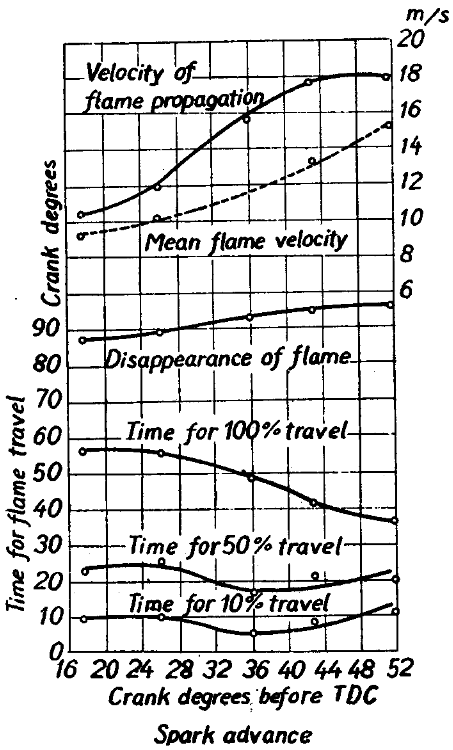

Fig. 10. Variation of time for flame travel and flame speed with spark advance

Engine speed: 860±50 rpm
Output : 0.85~0.9 HP
Throttle: 1/4
Air-fuel ratio: (10.3±0.6) : 1
Start of injection: 35° after TDC on the suction stroke

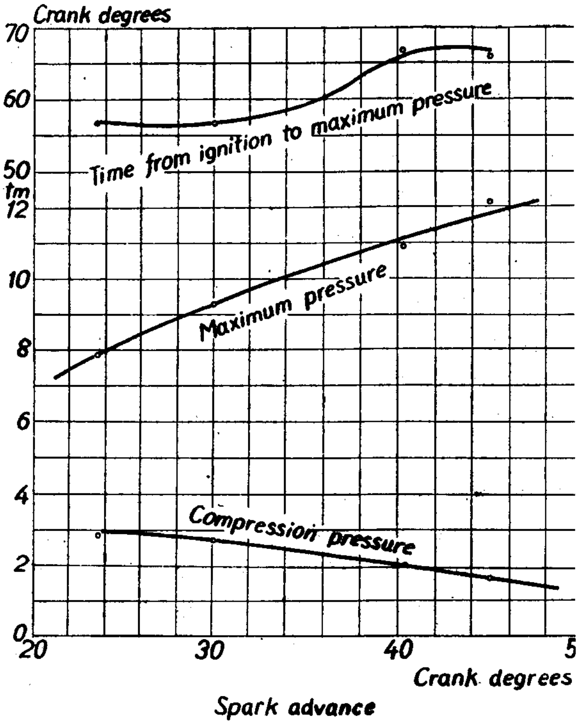

Fig. 11. Variation of maximum pressure and time from ignition to maximum pressure with spark advance

Engine speed: 1000±65 rpm
Output : 0.65~0.79 HP
Throttle: 1/4
Air-fuel ratio: (10.8±0.3) : 1
Start of injection: 35° after TDC

with the advancing of ignition. Comparing it with the time required for 50% travel, it is noted that the rate of flame propagation after 50% travel becomes rapid as the spark is advanced. This rapid flame propagation after 50% travel is based on the fact that the combustion is completed during the compression stroke. On the contrary, with late ignition, the flame propagation after 50% travel becomes slow, because it takes place in the expansion stroke.

The time from ignition to disappearance of flame and the time required to attain the maximum combustion pressure increase as the ignition is advanced. This tendency is in reverse to that of 100% flame travel, which means the increase of the after-burning when the spark is advanced, that is, the unburned charge existing after the flame front increases as the ignition is advanced. This trend differs from the results obtained already in a carburetor system.[3] From this result, it may be said that the gasoline injection engine is more sensitive to the ignition timing than the carburetor engine.

The velocity of flame propagation increases as the ignition is advanced to 44 degrees, however, with further advance it remains constant. Whereas, the mean flame velocity increases always with the increase of spark advance, because the rate of flame propagation in the end mixture becomes rapid as the ignition is advanced.

Maximum combustion pressure. It becomes higher and the pressure rise due to combustion increases as the ignition is advanced.

II. Flame Development and Combustion Heat in the Engine Cylinder

In the previous experiments, the flame photographs disclose only a part of the behavior of the flame. In order to clarify the relation between the flame development and the pressure rise, the process of flame development extending through the whole combustion space must be observed. This part provides the results based on the flame development in the cylinder of gasoline injection engine, and the relation between the flame development and the evolution of combustion heat is discussed.

A. Test Apparatus

Fig. 12 shows the arrangement of the test apparatus.

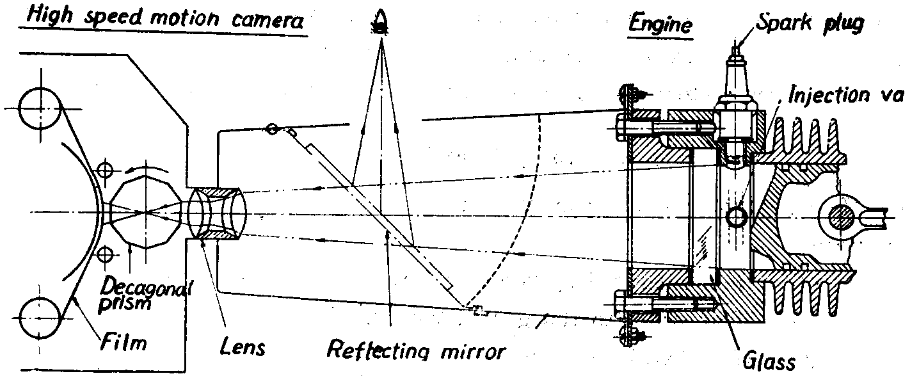

Fig. 12. Arrangement of test apparatus

(a) Test engine. A two stroke autocycle gasoline engine (air cooling, single cylinder, 67 mm bore, 76 mm stroke, and compression ratio of 4.3 : 1. The opening periods of exhaust and scavenging port being 72 and 64 degrees before BDC respectively.) was used.

The cylinder head of this engine is equipped with a heat proof glass window which allows an unobstructed view of the whole combustion chamber. In order to drive the engine by injecting the fuel into the cylinder, an injection pump of a Bosch type is installed at one end of the crankshaft and a Junkers injector is used. It is placed to direct the fuel spray in a plane perpendicular to the axis of the cylinder. Such a direction of the spray prevents it from sticking to the surface of the glass window, making it possible to drive the engine keeping the glass window clear.

(b) Recording apparatus. A high speed motion camera[2] is attached to the front of the engine to record the extending process of the combustion flame.

The pressure change is recorded with a photo-electric cell indicator used in connection with an electro-magnetic oscillograph.

(c) Test method. The light of ignition is so weak that it can not be photographed on the film. Therefore, in order to indicate the spark timing on the picture, a spark gap is installed in the camera and the discharge, which, of course, is devised to take place at the same instant with the ignition, is exposed.

As the combustion flame does not produce enough light to be recorded rapidly on the film, sodium carbonate dust is introduced into the intake manifold while the engine is running, so that the light of practically sufficient intensity for photographing purposes is obtained by its burning. The camera was operated at a speed of about 1000 frames per second. The pictures were taken on panchromatic 16 mm moving picture film. Fig. 13 presents typical records of a single explosion.

The records were taken varying the injection timing from 30 to 120 degrees before TDC, when the injection system is used. Further, to compare them with those in carburetor system, the same records were taken, using carburetor.

B. Analysis of Records

(a) Heat evolution due to combustion.

Notations.

Q_v = Heat liberated by the combustion of the mixture
Q_G = Heat given to the gas in the cylinder
Q_w = Heat lost by cooling
V = Cylinder volume at any crank angle
p = Pressure in the cylinder
T = Temperature in the cylinder
G = Total quantity of gas in the cylinder
T_w = Temperature at the inner surface of the cylinder
F = Cooling surface area in the cylinder
A = Heat equivalent of mechanical work
R = Gas constant
φ = Crank angle

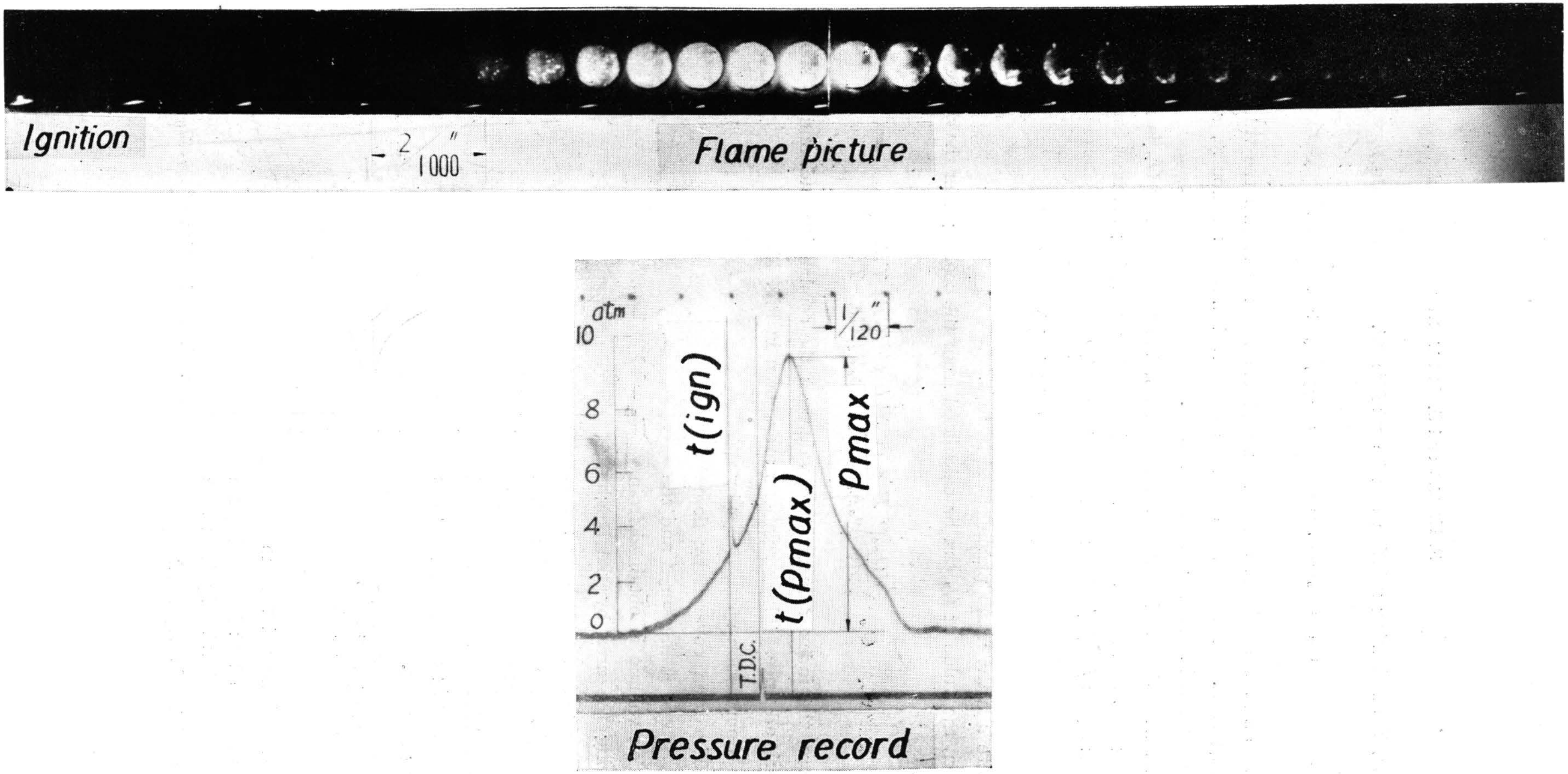

Fig. 13. Typical record of a single explosion

$t(ign)$=Ignition timing $t(p_{max})$=Time of p_{max}

Now, the following relation can be established.

$$Q_G = Q_v - Q_w = \frac{A}{\kappa-1}(pV - p_o V_o) + A\int_{Vo}^{V} pdV$$

Where κ is the adiabatic exponent, and the suffix o shows the values at the time of ignition. Therefore, Q_G can be evaluated without difficulty, since p, V can be calculated from the pressure record.

Now, in order to know the value of Q_v, the estimation of Q_w is necessary. Assuming that the Nusselt's experimental formula concerning the heat transmission coefficient $\alpha(kcal/m^2/h/^\circ C)$ at the cylinder wall.[4]

$$\alpha = 0.99\sqrt[3]{p^2 T}\,(1+1.24c)$$

where c is the mean piston speed in m/s.

Then, the value of Q_v can be calculated from the cooling after the combustion is over.

$$Q_w = \frac{dQ_{we}}{d\varphi}\int_{\varphi_o}^{\varphi} \frac{F}{F_e}\frac{p}{p_e}\left(\frac{V}{V_e}\right)^{\frac{1}{3}}\left(\frac{pV/GR - T_w}{p_e V_e/GR - T_w}\right)d\varphi$$

where, the index e means the values at the combustion end, and φ_0 shows the spark advance. These relations are shown in Fig. 14.

(b) Combustion space swept by flame. The area covered by flame on each frame is measured and the combustion volume is obtained from multiplying the area by the height of the combustion chamber at each crank angle. As discussed in the foregoing paper,[2] the inflamed charge is converted into the volume occupied at the time of ignition, applying the following relation.

$$\frac{V_{bo}}{V_o} = 1 - \frac{V_u}{V_o}\left(\frac{p}{p_o}\right)^{\frac{1}{m}}$$

where

V_u = non-inflamed volume

V_{bo} = volume that inflamed space occupied at the ignition time

m = polytropic exponent

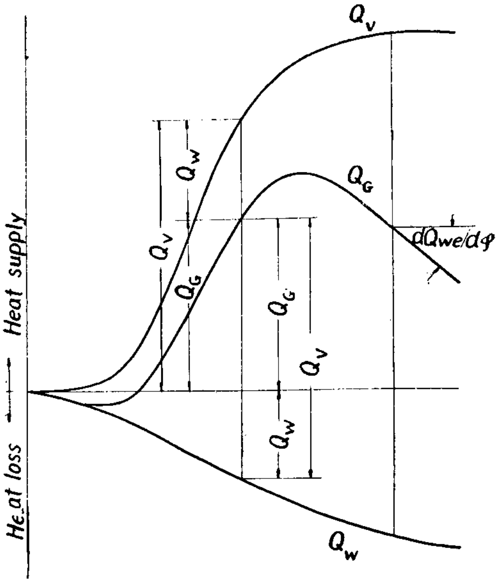

Fig. 14. Explanation of Q_G, Q_w and Q_v

C. Test Results

Fig. 15 shows the test results. As discussed in the previous paper, the straight line in the diagram shows the total energy of mixture contained in the given inflamed volume at any instant during an explosion. If, therefore, the explosive reaction is completed at the flame front, it indicates the relation between the heat evolution and inflamed volume. The data obtained from the experiment does not follow the straight line as indicated in the diagram. This difference shows that the unburned charge exists in the inflamed volume. In these results, the quantity of this unburned charge shows no definite trend for various starts of injections, although, in general, the large unburned charge exists after the flame front for the combustion in non-uniform mixtures.

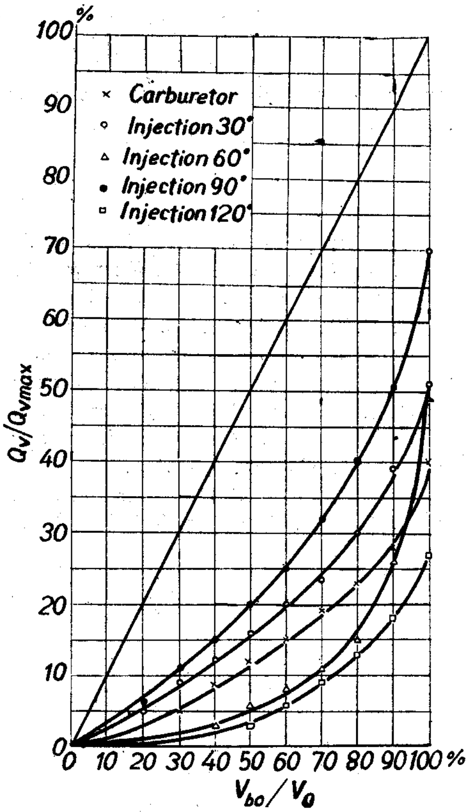

Fig. 15. Relation between Q_v/Q_{vmax} and V_{bo}/V_o

Summary

The test results may be summarized as follows:

(1) In the progress of combustion in the engine cylinder, the periods having a different rate of flame propagation can be defined, as pointed out in the previous paper.

(2) When the carburetor is used, the maximum combustion pressure is highest at the slightly richer air-fuel ratio than 11 : 1. With injection, however, it increases as the charge becomes rich and there is no tendency to decrease even at an air-fuel ratio of 10 : 1.

(3) With injection system, the initial combustion period of slow burning at the start of combustion and the time interval required for travelling the whole distance is shorter than with carburetion. When the carburetor is used, however, the combustion is completed almost at the flame front, but, with injection, combustion continues for some time after the flame front has passed.

(4) In the injection engine, the control of charging quantity is important to obtain an ignitable mixture at the spark gap. Further, the combustion state is varied by the slight change of spark advance, that is, the injection engine is sensitive to the ignition timing.

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