# On the Vaporization and Combustion Properties of Gasoline Spray

By

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(Received October, 1951)

## Introduction

Up to the present, the carburetor has been extensively used in the spark-ignition engine, and various improvements had been made by many investigators. The essential defects in the carburetor, however, can not be removed, and the carburetor system will become unsatisfactory owing to its defects with the progress of the engine performance.

On the other hand, when the injection system is employed, these defects are removed completely. Recently, several investigations on the gasoline injection system were carried out, but there still remains important problems which have not been clarified. When the fuel-air mixture is formed with carburetor, relatively uniform mixture may be obtained, because turbulence, which aids vaporization and mixing, occurs in the passage of gas through intake manifold and inlet valve. The injection of fuel into the cylinder, however, takes only a short time and allows poor turbulence to obtain a homogeneous distribution of fuel in the mixture, hence it is an important problem to investigate how the vaporization process of fuel spray takes place in the cylinder of the gasoline-injection engine. Further, it is important to secure the combustion properties of the mixture formed by the spray. In order to solve these fundamental problems, the fuel injected into a bomb filled with air at a desired density was ignited, and the effects of several factors on the process of vaporization and the extent of combustion were investigated.

## Part 1

### Vaporization Velocity and Combustion Pressure of Gasoline Spray

In order to investigate the vaporization and combustion properties of gasoline spray, an explosion bomb was employed, though the states in the bomb were somewhat different from those in the engine cylinder. The spray was formed in this bomb and the pressure due to the vaporization of fuel was recorded on the oscillograph by which the velocity of vaporization was measured. Further, the spray was ignited by spark and the properties of combustion were studied. In the engine cylinder, difficulties are encountered in the analysis of the behavior of the mixture, owing to the piston movement, however they were overcome by the use of the bomb.

## A. Apparatus and Method

A diagrammatic arrangement of the test equipment is shown in Fig. 1.

(a) Explosion bomb. The cylindrical bomb used for this experiment has inside diameter of 60 mm, length of 200 mm and volume of 0.6 liter. A Ni-Cr wire is wound around the outer shell of the bomb in order to heat the internal air. The experimental system consists of an injector, charging and exhaust valve, an injection

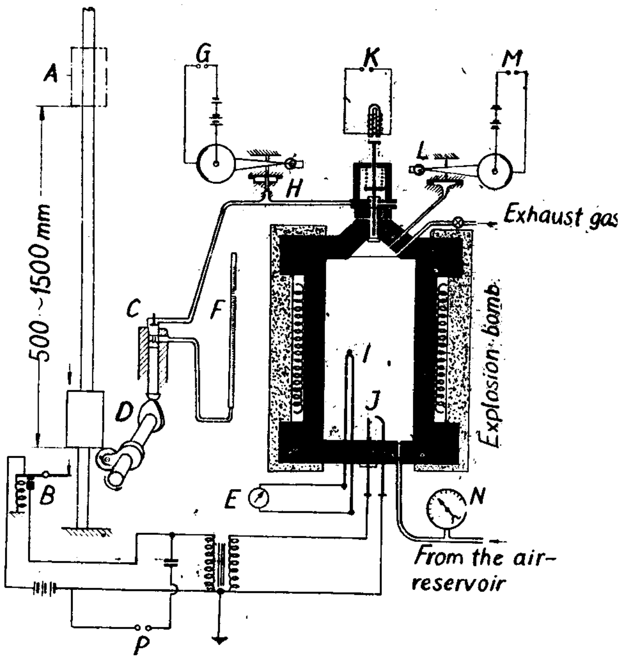


Fig. 1 Test equipment

| | |
|---|---|
| A | Falling weight |
| B | Breaker |
| C | Injection pump |
| D | Camshaft |
| E | Pyrometer |
| F | Burette for measuring the charging quantity |
| G | Amplifier for injection pressure recording |
| H | Injection pressure indicator |
| I | Thermocouple |
| J | Spark plug |
| K | Oscillograph<br>(Injection timing recording) |
| L | Combustion pressure indicator |
| M | Amplifier for combustion pressure recording |
| N | Pressure gauge |
| P | Oscillograph<br>(Spark timing recording) |

pump, a spark plug, a falling weight mechanism for operating the injection pump, and various measuring instruments. The charging and scavenging air is compressed by a compressor and stored in a reservoir before supplying in order to seperate oil, however no attempt was made to remove the vapour.

(b) Injection apparatus. An automatic spring loaded injector, having a single nozzle hole of 0.6 mm diameter (Bosch SDLos 64) is located at the center of the cover and the fuel is sprayed into the bomb through this nozzle by an injection pump (Bosch PEIS, dia. of plunger: 10 mm). When the falling weight strikes the actuating lever attached to the camshaft of the pump, it makes a single revolution and the fuel is sprayed. The speed of the camshaft can be regulated by changing the travel distance of the weight; the speed of 499 to 864 r. p. m. is obtained by the travel distance of 500 to 1500 mm. The mass of the weight is 12.6 kg, the momentum of which is enough for keeping speed constant during the injection period.

(c) Ignition apparatus. A battery ignition system is used. After the falling weight drives the camshaft it actuates the breaking device of the ignition system and the spark discharge follows at the spark gap. The timing of the spark with respect to the start of injection can be varied by changing the distance between the breaker and the camshaft.

(d) Measuring instruments. The initial air pressure in the bomb is measured by a pressure gauge installed before the charging port. The temperature is measured by a thermocouple, the hot junction of which is situated at the center of the bomb.

The pressure indicators used for measuring the pressure change of the gas in the bomb and of the fuel in the injection pipe are of a photo-electric cell type.

The timing of injection is known by the motion of the feeling pin of the injector: a magnetic coil is fixed near the feeling pin and the e. m. f. induced in the coil by the movement of the pin is measured.

(e) Test method. In the fuel-injection engine, the fuel is usually injected during the suction stroke, therefore the vaporization begins under nearly atmospheric pressure, and continues until the explosion starts in the high pressure. However, in this explosion test, it is impossible to change the pressure at injection and ignition period. Therefore, the fuel is sprayed into the air, the state of which would be encountered at the compression end of an engine. Hence the vaporization process may be different from that occurred in the cylinder.

The rate of vaporization was determined within the following conditions, under considerations that the vaporization takes place in the high pressure when the fuel spray is made in the compression stroke such as in the case of two stroke engine or supercharged one:

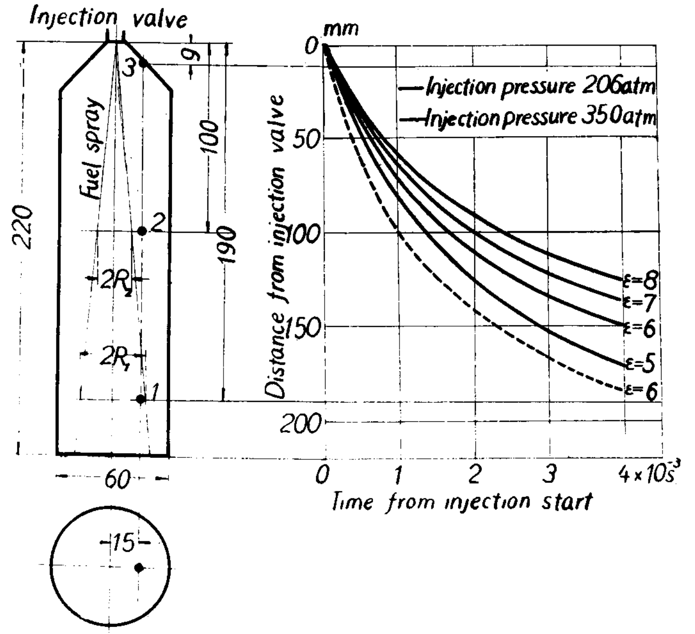
Initial temperature of air............24~300°C

Initial pressure of air..................atmospheric pressure and 4 atm.

In the combustion test, the initial conditions of air were chosen as shown in Table 1. These values correspond to the state of compression end, calculated on the assump-

Table 1.

| Initial pressure atm | Initial temperature °C | Corresponding compression ratio |
|---|---|---|
| 6 | 350 | 5 : 1 |
| 8 | 380 | 6 : 1 |
| 10 | 410 | 7 : 1 |
| 12 | 435 | 8 : 1 |



| Corresponding compression ratio | Injection pressure atm | Location of Spark gap | Radius of spray cone at the spark gap |
|---|---|---|---|
| 5 | 206 | 1 | $R_1$=12.8 |
| 6 | 206 | 1 | $R_1$=14.0 |
| 7 | 206 | 1 | $R_1$=14.8 |
| 8 | 206 | 1 | $R_1$=15.8 |
| 6 | 206 | 2 | $R_2$= 7.4 |
| 6 | 350 | 2 | $R_2$= 8.8 |

Fig. 2 Location of spark gap and distribution of fuel spray

tion that the compression in the cylinder follows the polytropic process with exponent of 1.3, and the temperature and pressure at the start of compression is 100°C and 0.9 ata respectively. The appearance of the distribution of fuel spray injected into the air at each of these density is shown in Fig. 2.[1]

Gasoline for automobile use, hydrogenated Diesel oil, heavy oil and water were used throughout the test. The properties of these samples are listed below.

Table 2. Properties of samples.[2]

| Kind of sample | Distillation characteristics | | | Specific gravity at 22°C | Heat of vaporization kcal/kg | Specific heat kcal/kg °C | |
|---|---|---|---|---|---|---|---|
| | First drop °C | Distillated quantities until 100°C % | End point °C | | | Liquid state | Vapour state |
| Gasoline | 42 | 60 | 144 | 0.728 | 82 | 0.45 | 0.36 |
| Hydrogenated Diesel oil | 146 | — | 330 | 0.773 | 77 | 0.42 | 0.35 |
| Heavy oil | 206 | — | 390 | 0.986 | 64 | 0.41 | 0.33 |
| Water | | 100 | | 1.00 | 569 | 1.00 | 0.46 |

## B. Test Results and Discussions

(a) Effects of some variables on the rate of vaporization.

When the fuel is injected into heated air in the bomb, the decrease in pressure accompanies the decrease in temperature of the air caused by the flow of heat required for temperature rise and vaporization of the droplets of spray. The experimental method employed in this investigation consists in recording the pressure decrease following the injection of fuel. From the records, the rate of vaporization was calculated, and the effects of initial pressure, temperature of air and volatility of fuel were investigated.

(1) Calculation of vaporization interval. A typical photographical record is presented in Fig. 3. The $V$-, $P_e$- and $P_v$-curve indicates the injection time, the

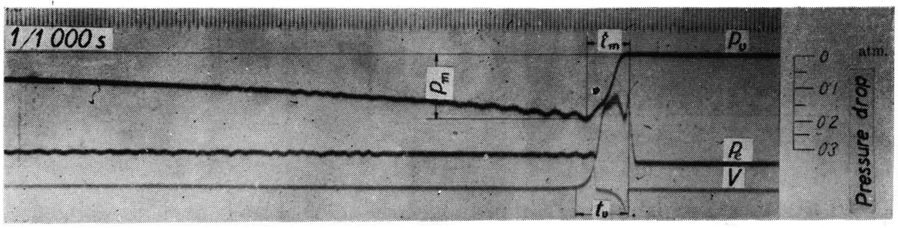


Fig. 3 A typical pressure record

(Pressure drop due to vaporization of fuel)

$t_v$=Duration of fuel injection
$t_m$=Time elapsing between injection and minimum pressure
$P_m$=Pressure drop

injection pressure and the gas pressure in the bomb respectively. From the inspection of the record, the pressure decrease begins at about 1/1000 second after the first part of the fuel is charged into the bomb, and after the minimum pressure is attained, it rises gradually until it shows the higher pressure than its initial value. This pressure rise occurs due to the vapour pressure of the fuel.

After the end of vaporization, the temperature of the mixture rises due to the heat transmited from the wall of the bomb. The time when the vaporization completes is some time later than that when the minimum pressure is attained, owing to the heat transfered from the bomb wall. Let $dQ$ be the heat transfered to the fuel from the unit quantity of mixture at the time interval $dt$, then the following equation can be established:

$$GdQ = -Gc_{vm}dT + \alpha F\ (T_0 - T)\ dt$$

where, $G$=quantity of mixture included in the bomb
$c_{vm}$=mean specific heat of the mixture by constant volume
$F$=surface area of heat transfer
$T$=variable temperature of the mixture
$T_0$=temperature at the inside of the wall
$\alpha$=coefficient of heat transfer at the wall surface
$t$=time interval elapsing from the start of injection

Assume that the heat capacity of the bomb wall is extremely great compared to the heat transfered to the fuel, that the temperature of the inner surface of the wall is kept always constant, and that the vapour pressure can be neglected, then

$$\frac{1}{p_0 - p}\frac{dp}{dt} = -\frac{1}{p_0 - p}\frac{GR}{c_{vm}V}\frac{dQ}{dt} + \frac{\alpha F}{Gc_{vm}} \tag{1}$$

where, $p$=variable pressure of the mixture
$p_0$=initial pressure
$V$=total volume of the bomb

Since $dQ=0$, when the vaporization ends, equation (1) can be modified into

$$\frac{1}{p_0 - p}\frac{dp}{dt} = \frac{\alpha F}{Gc_{vm}} \tag{2}$$

These relations indicate that the formula (1) exists while the vaporization is proceeding, whereas after the vaporization is completed it can be written as (2). Therefore the time interval required for vaporization can be determined by calculating the value of $1/(p_0 - p)\cdot dp/dt$ from the pressure curves.

(2) Effect of air temperature and pressure on the vaporization of gasoline spray. In Fig. 4 and 5 is shown the effect of air temperature on the rate of

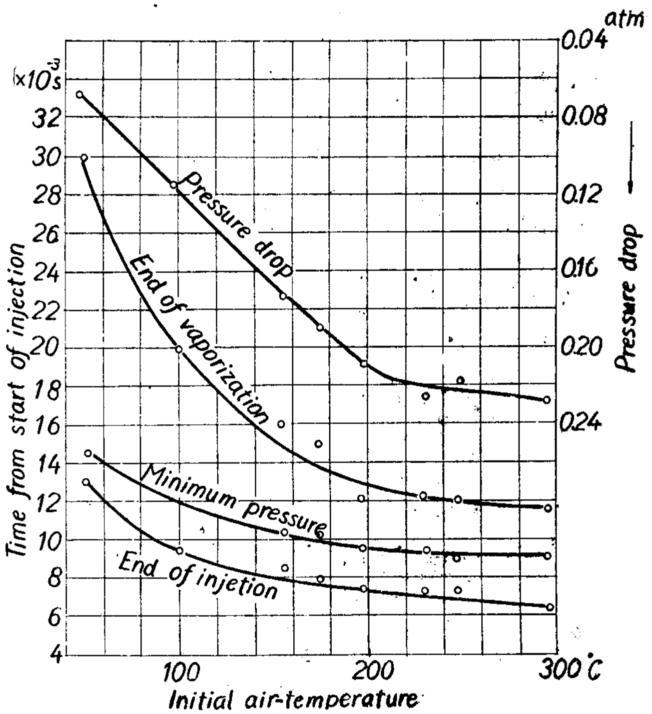


Fig. 4 Effect of initial air-temperature on vaporization of fuel spray
Initial air-pressure: 4 atm, Injection pressure: 206 atm

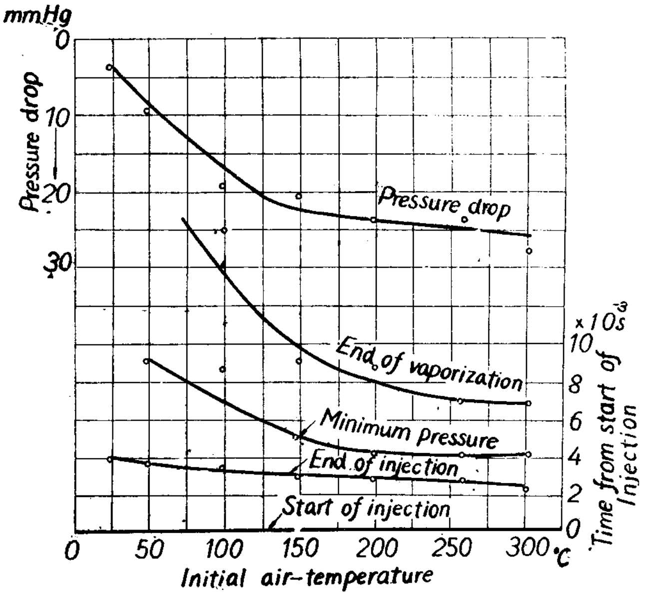


Fig. 5 Effect of initial air-temperature on vaporization of fuel spray
Initial air-pressure: 749 mm Hg, Injection pressure: 203 atm, Air-fuel ratio: (7.6±0.6) : 1

vaporization. With the increase of the initial temperature, the maximum value of pressure drop increases. The time required for vaporization decreases as the temperature increases and as the pressure decreases.

(3) Effect of fuel volatility on the vaporization. One of the most important characteristics of fuel concerning vaporization is its boiling point. In order to clarify this effect, the rate of vaporization was determined, using the fuels with different distillation characteristics as shown in Table 1.

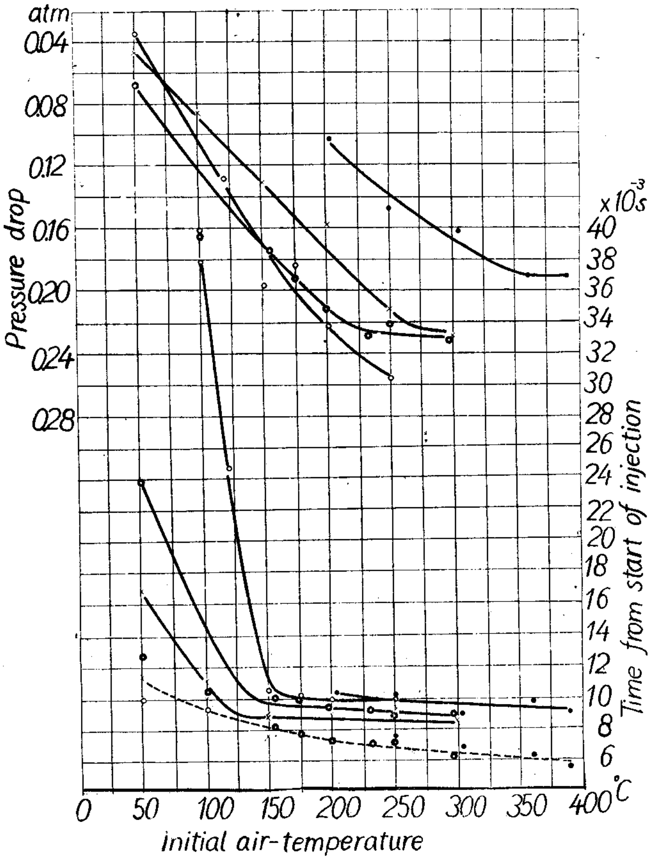


Fig. 6 Rate of vaporization for each fuel

Initial air-pressure: 4 atm
Injection pressure: 206 atm

○ Water . . . . . . . . . . . . . . Air-fuel ratio ( 7.9±0.4) : 1
● Heavy oil . . . . . . . . . . . . Air-fuel ratio ( 6.2±0.7) : 1
× Hydrogenated Diesel oil . . . Air-fuel ratio (10.4±0.8) : 1
◎ Gasoline . . . . . . . . . . . . Air-fuel ratio (10.4±0.7) : 1

The effect of fuel volatility on the vaporization is shown in Fig. 6. The amount of the pressure drop is greatest with water and least with heavy oil. Therefore, it will be noted that the greater the vaporization heat the more the heat taken away from the mixture. The early beginning of the pressure drop occurs with the fuel containing distillates of low boiling points such as gasoline, whereas it reverses with fuels having a high first boiling point such as heavy oil. For gasoline, hydrogenated Diesel oil and heavy oil, an increase of air temperature at first increases the pressure drop with nearly the same gradient, but at above certain temperatures it is kept almost constant. This temperature is higher when fuel is less volatile. For water, there is no tendency to become constant. These facts will be explained by analysing the vaporization process.[3] The time interval between injection start and occurrence of minimum pressure, decreases rapidly with an elevation of initial temperature; however it does slowly above 200 °C.

(b) Combustion properties in the explosion bomb.

(1) Analysis of the pressure records. A typical record of the explosion is shown in Fig. 7. On the record, the line of $V$, $Z$, $P_e$, $P_v$ shows the injection time, spark time, injection pressure and combustion pressure respectively. Each characteristic point is designated on the record. A slight decrease at the pressure line which continues for some time after the start of injection indicates the pressure drop caused by the vaporization of gasoline, as described above.

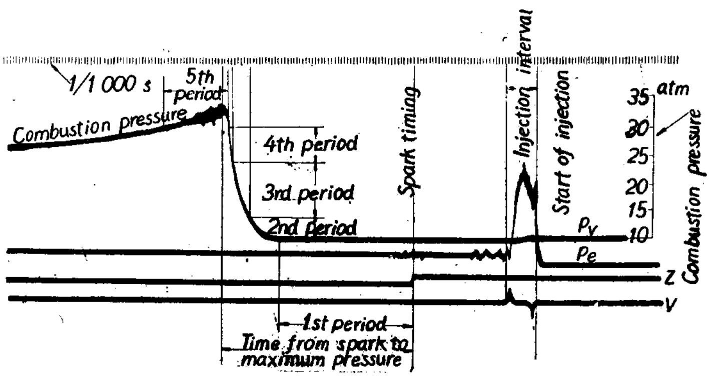


Fig. 7 A typical combustion pressure record

Let $dQ$ be the heat liberated by the combustion of the unit quantity of the charge during $dt$. Assume that the temperature of the whole mixture increases uniformly as soon as the heat is supplied. Then

$$GdQ = Gc_{vm}dT + \alpha F\ (T - T_0)\ dt$$

where, $t$=time interval elapsing from the occurrence of the spark. The other symbols are the same with that in the case of vaporization. Then,

$$-\frac{1}{p-p_0}\frac{dp}{dt} = -\frac{1}{p-p_0}\frac{GR}{c_{vm}V}\frac{dQ}{dt} + \frac{\alpha F}{Gc_{vm}} \tag{3}$$

When the combustion completes,

$$-\frac{1}{p-p_0}\frac{dp}{dt} = \frac{\alpha F}{Gc_{vm}} \tag{4}$$

Hence, if the value of $-1/(p-p_0)\cdot dp/dt$ is calculated from the pressure curves, the time when the combustion ends can be determined.

Now, from equation (3)

$$\frac{dQ}{dt}=\frac{c_{vm}V}{GR}\frac{dp}{dt}+\frac{\alpha FV}{G^2R}(p-p_0) \tag{5}$$

$$Q=\frac{c_{vm}V}{GR}(p-p_0)+\frac{\alpha FV}{G^2R}\int_0^t (p-p_0)\,dt \tag{6}$$

Estimate the value of $\alpha$ after the end of combustion from equation (4)

$$\alpha=\frac{c_{vm}G}{F}\frac{1}{t-t_e}\ln\frac{p_e-p}{p-p_0} \tag{7}$$

where, $t_e$=time at which the combustion is over

$p_e$ = pressure at $t_e$

If the assumption is permitted, that the coefficient of heat transfer during the combustion is equal to that after the end of combustion, $dQ/dt$ and $Q$ can be calculated, applying $p$ and $dp/dt$ obtained from the pressure record to equations (5) and (6). $dQ/dt$ may be considered proportional to the rate of mass burned in the mixture. It is called the rate of combustion in this paper.

An example of $dQ/dt$ and $Q$ is illustrated in Fig. 8. Except some special cases, the following time intervals more or less clearly defined are designated in the combustion of the gasoline spray.

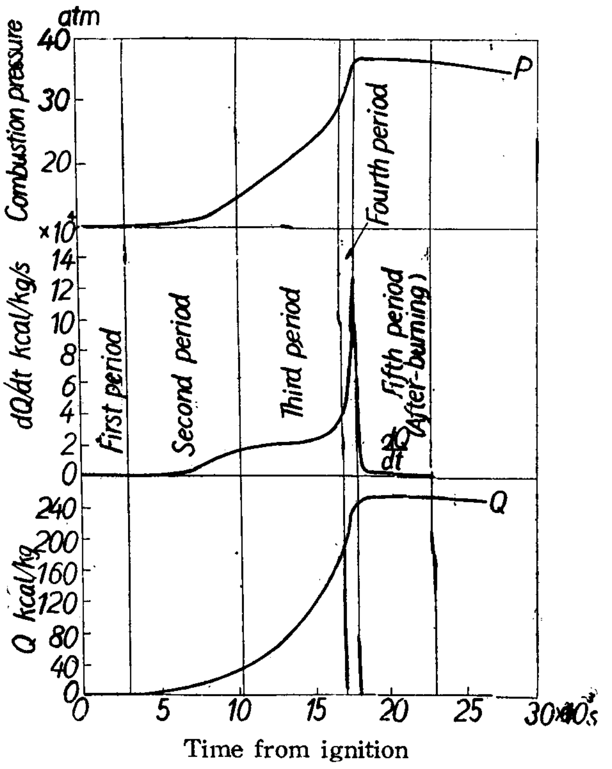


Fig. 8 $p$, $dQ/dt$, and $Q$

*First period.* This is the time interval between the spark and the beginning of a perceptible pressure rise, and is indicative of slow combustion immediately after ignition spark. As $dQ/dt=0$, the pressure rise does not occur.

*Second period.* This is the time interval from the start of pressure rise until the beginning of the state of constant rate of combustion. During this period, the rate of combustion increases.

*Third period.* In this period, the rate of pressure rise is almost constant; i. e., the stationary rate of combustion occurs.

*Fourth period.* In this period, the rate of combustion reaches its maximum, owing to the increase of pressure and temperature of the unburned mixture by the preceding combustion. Sometimes reaction is so intense in this period that the detonation occurs accompanying so-called knocking sound.

*Fifth period.* (*After-burning period.*) This period is indicative of after-burning. The most part of the mixture has already burned before this period and the mixture near the wall burns slowly in this period. Furthermore, since the cooling loss at the wall increases, the pressure change is very slow. Severe vibrations are set up in this period, when the knocking combustion occurs.

The curve of $dQ/dt$ described here can be seen in the typical cases; however, different processes occur corresponding to the different state of combustion.

(2) Effect of air-fuel ratio on the combustion. The effect of

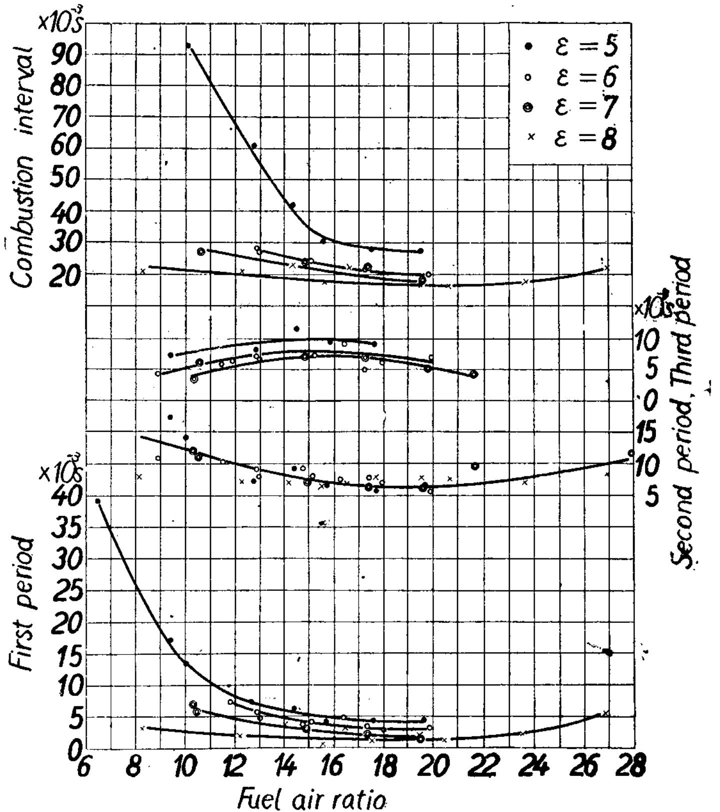


Fig. 9 Combustion time

Injection pressure: 206 atm
Spark timing: (38±4) ×10⁻³ sec.
Location of spark gap: 1 in Fig. 2

the mixture ratio is as follows:

*First period.* Fig. 9 shows the duration of the first period as affected by mixture ratio. It becomes minimum at an air-fuel ratio of about 19:1 at any compression ratio, i. e., it is lengthened in rich or lean mixture, this effect being more marked at low compression ratio. It is probably caused by the fact that the range of inflammability is reduced at lower compression ratio.4) It is reasonable that the induction period is lengthened near the upper and lower ignition limits.

*Second period.* In Fig. 9, the duration of this period is shown. It exhibits no definite trend with the compression ratio, and attains minimum at the air-fuel ratio of about 19:1. During this period, the combustion is extended acceleratively; however the pressure rise is slow and the same trends are observed as in the previous period.

*Third period.* As the combustion extends at nearly constant speed in this period, the progress of pressure rise is influenced essentially by the compression and the mixture ratio. Within the lower compression ratio, this period can be defined clearly, while with its increase the rate of pressure rise becomes greater, until at the compression ratio of 8:1 the combustion becomes so intense that it is difficult to distingiush this interval from the following period.

In Fig. 9, the third period is shown. It decreases with increased compression ratio, and attains maximum at the air-fuel ratio of 15~16:1. The mixture ratio for the maximum duration is richer when the compression ratio is lower.

*Total combustion interval.* The combustion interval is shown in Fig. 9. It attains minimum at the air-fuel ratio of nearly 19:1, and is shortened as the compression ratio increases. This fact means that the velocity of combustion progress is maximum at this air-fuel ratio. It is a noticeable fact that the mixture ratio at which the combustion velocity attains maximum is different from that in an engine cylinder. The combustion interval is influenced most at the first and the second period, and it will be noticed that the combustion interval is controlled by the initial combustion period

*Pressure rise due to combustion.* In Fig. 10, the effect of compression and mixture ratio on the pressure rise at each period is shown. The pressure at the end of the second period is minimum at the air-fuel ratio of 13~14:1, however in the range of leaner mixture it remains nearly constant. The pressure attained at the end of the third period is maximum at a certain air-fuel ratio for each compression ratio and its mixture ratio becomes weaker as the compression ratio increases. When the mixture becomes richer above it, the pressure rise after the fourth period increases until at last the pressure vibration occurs accompanying knocking and the extremely high maximum pressure. Such mixture ratio that gives the great pressure rise at the fourth period becomes lean as the compression ratio increases.

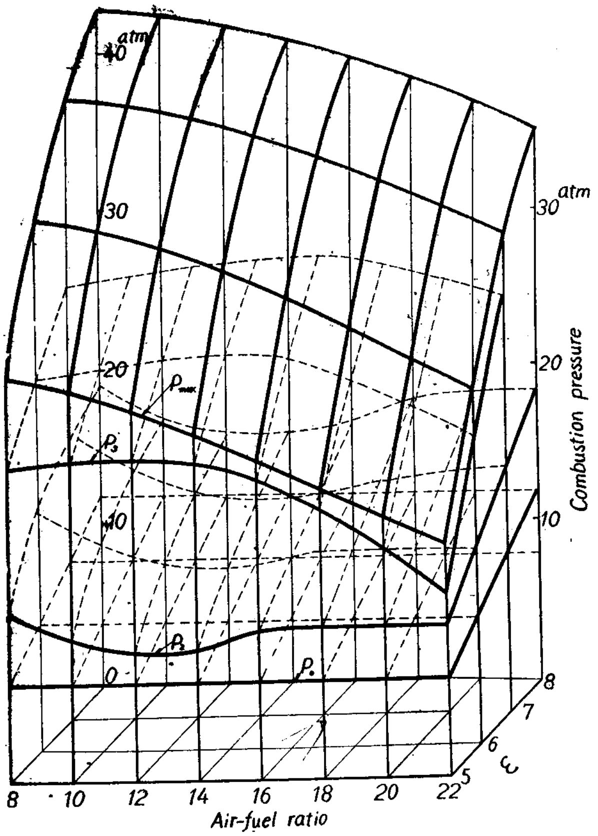


Fig. 10 Combustion pressure

Injection pressure: 206 atm
Spark timing: $(38\pm4)\times10^{-3}$ sec.
Location of spark gap: 1 in Fig. 2
ε: Compression ratio

$p_0$ .... Initial pressure
$p_2$ .... Pressure at the end of 2nd period
$p_3$ .... Pressure at the end of 3rd period
$p_{max}$ ... Maximum pressure

The maximum combustion pressure increases steadily as the concentration of fuel increases, regardless of compression ratio. In the delayed ignition (spark occurring several minutes after injection), however, the maximum pressure reaches its maximum at 10~20% richer air-fuel ratio than the theoretically correct one.[5] The difference between these two cases is caused by the distributing state of fuel vapour in the mixture. Within the range of ignition time experimented here, distribution of fuel vapour is not yet uniform, because no active turbulence exists in the medium, and all the available oxygen is not consumed.

*Rate of combustion.* As shown in Fig. 11, the value of $(dQ/dt)_{max}$ increases as the compression ratio and the charging quantity increase. When $(dQ/dt)_{max}$ is greater than $12\times10^4$ kcal/kg/s, pressure vibration occurs. Further, the heat liberated during the after-buring period increases as the compression ratio and fuel concentration become high. This is expected by the reason that the distribution of fuel vapour is poorer as the compression ratio and the charging quantity increase because the completion of the vaporization is delayed, and that the initial combustion becomes imperfect. In the above experiments, the mixture in the immediate neighbourhood of the spark gap at the spark time is richer than that indicated by the ratio of the air-fuel quantities, because ignition is possible with an apparently leaner mixture than the lower limit of ignition. Therefore, the so-called stratification of the mixture is within the bounds of possibility and the properties above mentioned are the characteristics in the stratificated mixture, i. e., in this experimental condition, the most suitable distribution of mixture for the extent of initial combustion was formed at an air-fuel ratio of 19 : 1. In the engine cylinder, however, the distribution of mixture should be complicated, owing to the turbulence, which aids further mixing effects.

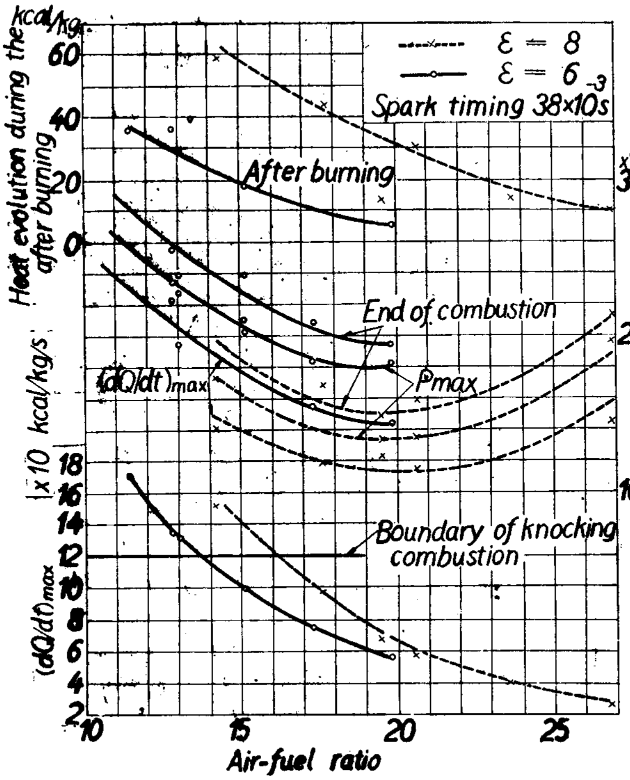


Fig. 11 Effect of air-fuel ratio on rate of combustion

(3) Effect of spark timing on the combustion. An analysis of the significance of the spark time variable presents the following effects : (1) change in the distribution of fuel with a consequent change in the air-fuel ratio at the point of ignition; (2) increase in quantity of fuel vaporized within the range of very early ignition, which may involve a change in the ratio of air to fuel vapour. If suffi-

cient time to elapse between injection and ignition is allowed, the homogeneous mixture can be obtained, however, in this experiment, it was not investigated.

The mixing state of fuel and air differs locally. Further, the distribution of spray is varied with the injection pressure. In order to clarify the effect of the mixing state of fuel and air on the combustion, experiments for various ignition time were carried out changing the location of spark gap and the injection pressure.

*Combustion interval.* The time interval elapsing from the spark to the attainment of maximum pressure is plotted against spark timing in Fig. 12 and 13. When the spark is delayed, it is lengthened, however with further delayed spark it is shortened again, until self-ignition occurs. When the spark advances, relatively good mixture for the extent of initial combustion is formed at the neighbourhood of the spark gap, therefore the combustion is promoted.

When the ignition occurs at the location of 2, the combustion interval is slightly reduced as compared with that ignited at the position 1. Further, in this case the early ignition becomes reliable, whereas the later ignition is very unreliable and the range of the reliable ignition time is reduced. This is due to the fact that the fuel spray passes through the neighbourhood of the spark gap and the inflammable mixture can not be formed at the spark gap. The reliable range of ignition, however, is remarkably extended and the combustion interval is reduced at the injection pressure of 350 atm. From this point of view the high injection

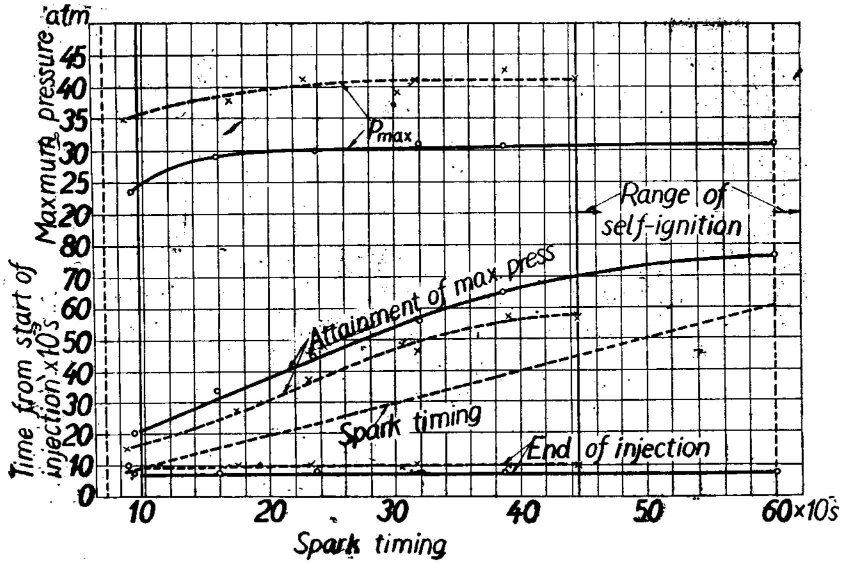


Fig. 12 Effect of spark timing on combustion

—— $\varepsilon=6$, - - - $\varepsilon=8$

Air-fuel ratio: 12:1, Injection pressure: 206 atm, Location of spark gap: 1 in Fig. 2

pressure is necessary when the fuel injection engine is running at high speed or when the injection is delayed.6) It is obvious from Fig. 13, that the combustion time is lengthened when the ignition is extremely advanced, showing that the vaporization has not yet completed at the spark time and the ignition takes place in the liquid-vapour-air mixture.

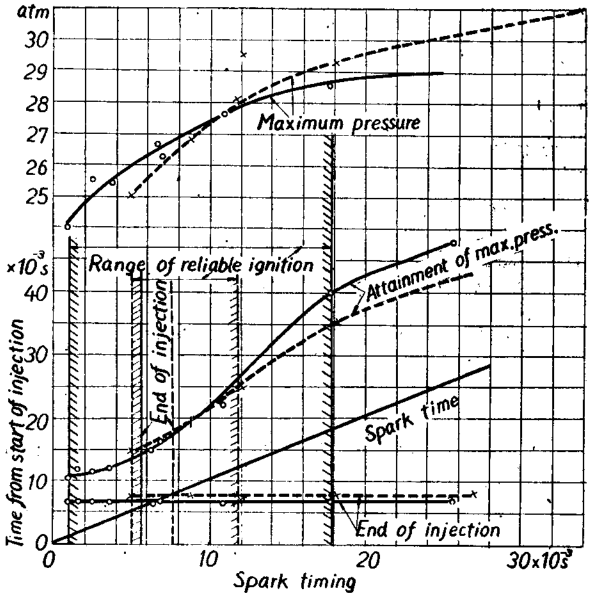


Fig. 13 Effect of location of spark gap and injection pressure
—— Injection pressure: 350 atm, - - - Injection pressure: 206 atm
$\varepsilon=6$, Air-fuel ratio: $(12.6\pm0.6):1$,
Location of spark gap: 2 in Fig. 2

*Combustion pressure.* As the time between injection and the discharge of the spark increases the maximum pressure increases, because the distribution of fuel vapour becomes more uniform; whereas with further delayed ignition it does not increase. This fact means that within such a late spark range, the mixing of fuel vapour in the air at the moment of spark is much improved. The ignition time at which no increase of the maximum pressure appears is later as the compression ratio is higher. This is caused by the fact that the longer interval is necessary to complete the vaporization at higher compression ratio.

*Rate of combustion.* Fig. 14 shows the progress of $dQ/dt$ in the combustion at an early and a late ignition respectively. At the early ignition the rate of increasing of $dQ/dt$ is high, and $(dQ/dt)_{max}$ appears early; however its absolute value is smaller and the after-burning period is longer than when the ignition is delayed. Fig. 15 shows the influence of ignition time on the rate of combustion. The maximum rate of combustion increases rapidly as the ignition is delayed and at last knocking occurs. This must be the result of the occurrence of self-ignition of the end gas, the temperature of which has been raised during the long time interval preceding this period. In this case also, when $(dQ/dt)_{max}$ is greater than $12\times10^4$ kcal/kg/s, the knocking combustion occurs as shown in the diagram. From these results, it will be noted that $(dQ/dt)_{max}$ of $12\times10^4$ kcal/kg/s is the

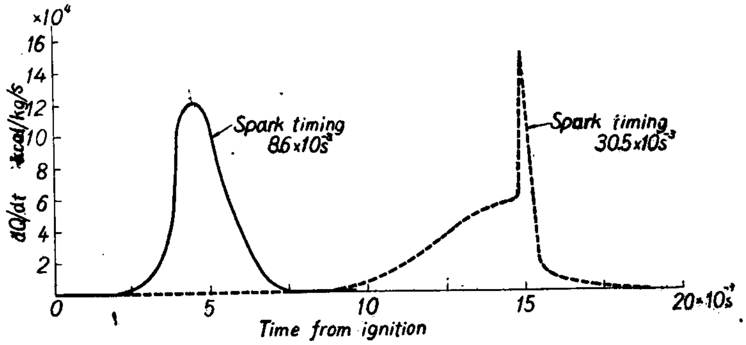


Fig. 14 Effect of spark timing on rate of combustion

Initial air-pressure: 12 atm
Initial air-temperature: 420°C
Air-fuel ratio: 12 : 1

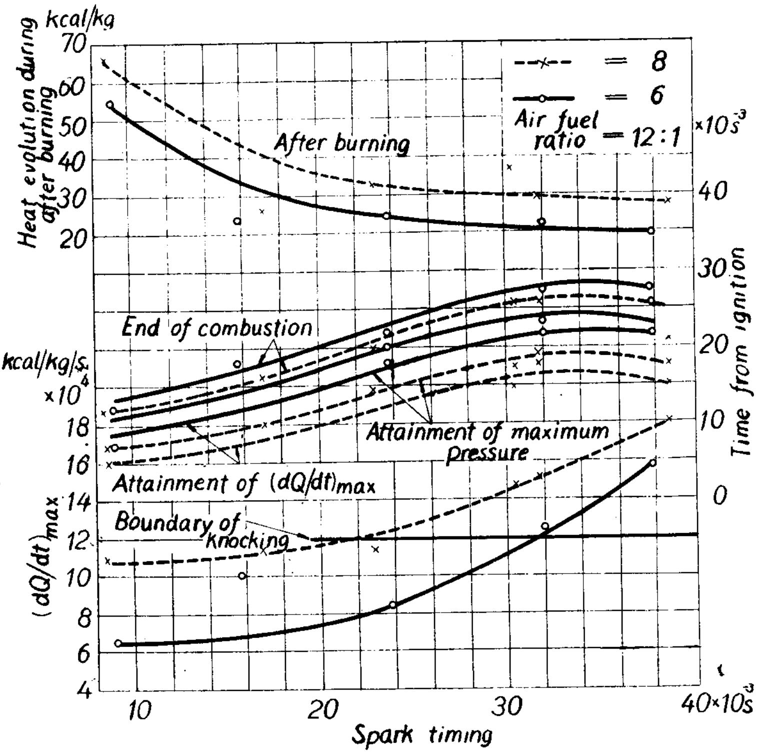


Fig. 15 Effect of spark timing on rate of combustion

knocking limit for the combustion of the mixture. Since $(dQ/dt)_{max}$ decreases as the distribution of fuel vapour becomes poor, it is concluded that the fuel injection engine is better than the one using carburetor as far as knocking is concerned. However, the heat of after-burning becomes great when the spark is advanced.

Further, the knocking combustion is hard to occur when the spark gap is located at 2. This is caused by the reason that the travel distance of the combustion flame from spark gap is reduced.

## Part 2

## Extent of Combustion Flame and Development of Combustion Pressure

In a spark ignition engine, the extent of combustion is the chief factor to control the rate of pressure rise, hence it has an important influence on the engine performance. In order to clarify the relation between the extent of combustion flame and the pressure rise when gasoline spray is ignited, the flame development in the bomb was photographed through a glass window.

### A. Apparatus and Method

The test arrangement is shown in Fig. 16.

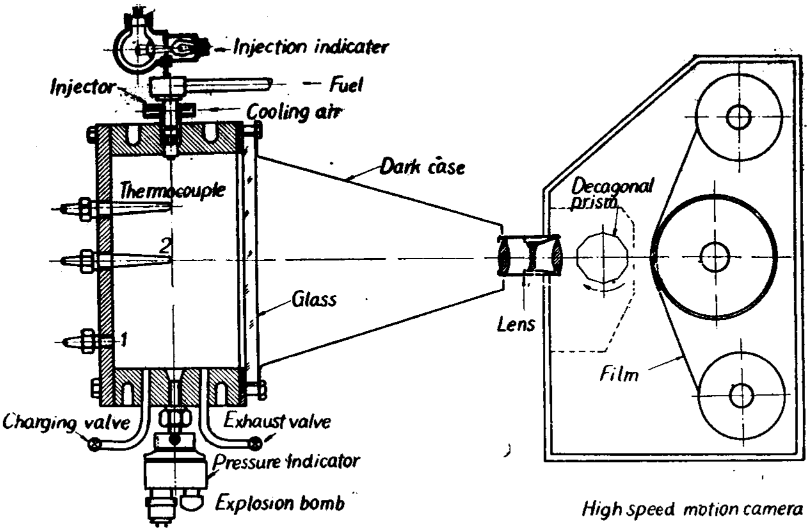


Fig. 16 Diagrammatic sketch of the test apparatus

(a) Explosion bomb. A cubic bomb used for this experiment has volume of 2 liters; 100 mm × 200 mm rectangle and 100 mm depth. One side of this bomb is equipped with a glass window large enough to cover the entire combustion space, through which the flame movement can be observed. The rest of the walls is surrounded with air jackets through which the hot air is supplied from the air heater and the temperature is kept constant as far as possible. The charging air is heated up to the desired temperature in another bomb and is supplied into the bomb through a heat-insulated pipe.

(b) Photographing apparatus of flame. The high speed motion camera was employed to record the extending process of the combustion flame. Its essential parts are shown in the diagram; the decagonal prism revolves in front of the film keeping a constant revolving ratio to the feeding speed of the film. With such a system, the image remains at rest with respect to the film despite of its movement. Therefore, the image photographed has slight distortion if there are movements in the object.

(c) Indication of injection timing. The start of injection was marked by recording the motion of the needle valve of the injector using a photo-electric cell as illustrated in the diagram.

The other measuring methods, unless stated here, are the same with those used in the foregoing experiments.

(d) Test method. As the light of the ignition spark is so weak that it can not be photographed on the film, a small mercury lamp which is made to emit at the same instant of spark was equipped near the bomb and its discharge glow was photographed.

As the combustion flame also does not produce enough light to be recorded rapidly on the film, sodium carbonate dust is supplied in the bomb before explosion. Thus, practically sufficient intensity for photographing purpose is obtained due to its burning.

The pictures were taken on 16 mm moving picture film, operating the high speed camera at about 800 frames per second. The typical records of an explosion are reproduced in Fig. 17. The sections on the flame picture show 10 mm square.

The kinds of gasoline employed are of regular commercial use and of aircraft one. The principal properties of these fuels are listed below.

Table 3. Properties of fuels.

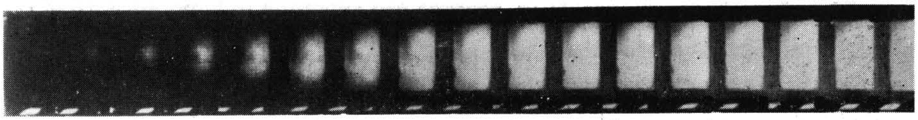
| Kind | Specific gravity (at 30°C) | Distillation characteristics | | Reid vapour pressure (at 38°C) | Octane number |
|---|---|---|---|---|---|
| | | First drop °C | End point °C | | |
| Commercial gasoline | 0.745 | 42 | 217 | 0.28 | 54 |
| Aircraft gasoline | 0.728 | 51 | 146 | 0.32 | 78 |

In this experiment, as it is dangerous to raise the initial air pressure in the bomb the experiment was carried out under the atmospheric pressure, varying the initial temperature, air-fuel ratio and spark timing.

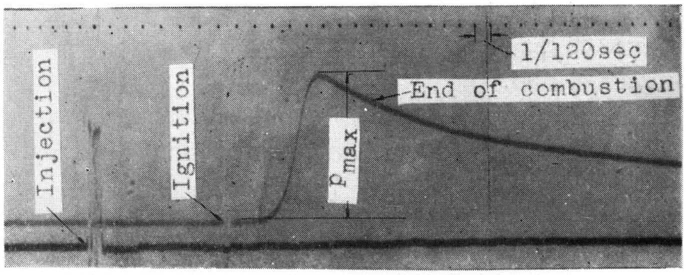
## B. Test Results

(a) Analysis of flame picture and pressure record.

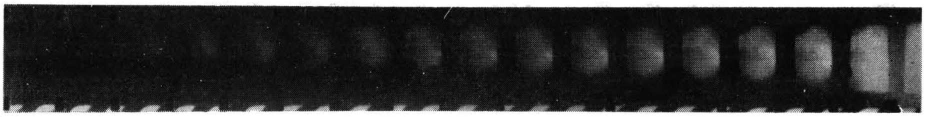
*Determination of inflamed space.* The area covered by flame on each frame of the picture is measured and the inflamed space is obtained from multiplying it by the thickness of the combustion chamber. The space swept by flame, estimated by such a method, is the value at the moment of exposure. The burning gas expands and pushes the unburned fraction ahead of it, therefore the pressure as



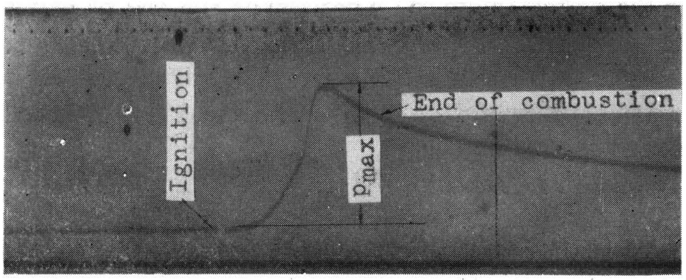
Flame picture



Pressure record
Combustion in non-uniform mixture



Flame picture



Pressure record
Combustion in uniform mixture

Fig. 17 Typical records for the combustion in uniform and non-uniform mixture.

well as the temperature of the unburned gas rises as the flame progresses.

On account of this fact, the inflamed volume does not indicate the inflamed mass. Therefore, it is reasonable to convert the inflamed volume into that occupied under the same density. In this paper, the volume swept by flame at any given time was changed to that which would be occupied at the time of ignition. The calculation was made as follows.

Let $V_b$=inflamed volume in a frame
$V_u$=non-inflamed volume in a frame
$p$=pressure in the bomb at the moment of exposure
$V$=volume of the bomb
$p_0$=initial pressure
$V_{b0}$=volume which $V_b$ occupied at the moment of ignition

Assuming that the unburned gas is compressed adiabatically, then

$$\frac{V_{b0}}{V}=1-\frac{V_u}{V}\left(\frac{p}{p_0}\right)^{\frac{1}{\kappa}}$$

The value of $V_{b0}/V$ shows the fractional mass of charge inflamed if the mixture is completely homogeneous. In this experiment, however, since the mixture is non-uniform, it does not indicate the true burned mass, but it indicates how much mixture is inflamed in each frame.

*Errors occurred in the flame picture.* In the flame picture, the exposure of a frame begins at the moment when a previous frame finishes its exposure. Therefore, the exposure of a frame is given during the time interval corresponding to the distance between each frame. Hence, the movement of flame during the exposure interval is photographed, and some distortion appears in the picture. This time interval is about 1/800 sec. Further, since the forward edge of the flame front in the picture indicates its position at the end of exposure, there is the difference of time between the exposure of the left and the right side of a frame, which corresponds to its breadth. This time difference is $0.8\times10^{-3}$ sec.

The other possible sources of errors occurred in the determination of the inflamed volume are as follows.

(i) $V_b$ is obtained by multiplying the development area of the flame by the thickness of the bomb. Hence, as the irregularity of the flame front in the direction of the thickness of the bomb is not considered, some errors due to the irregular shape of the flame front should have occurred. As the position of the flame front recorded in each frame indicates the most advanced edge of the flame front, the real inflamed volume should be somewhat smaller than the measured results.

(ii) In some cases the flame front can not be determined very well, owing to the bluring of the picture.

*Process of heat evolution.* The heat liberated by combustion ($Q_v$) can be determined by equation (6), using the pressure records, In Fig. 18, a typical set of graphs of $V_b/V$, $V_{b0}/V$, $(p-p_0)/(p-p_0)_{max}$ and $Q_v/Q_{vmax}$ is shown, where $Q_{vmax}$ shows the total heat evolution.

### (b) Relation between flame development and heat evolution at various conditions.

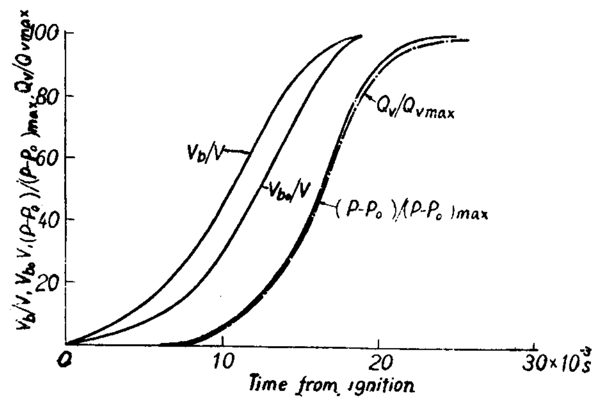


Fig. 18 Typical example of combustion extent

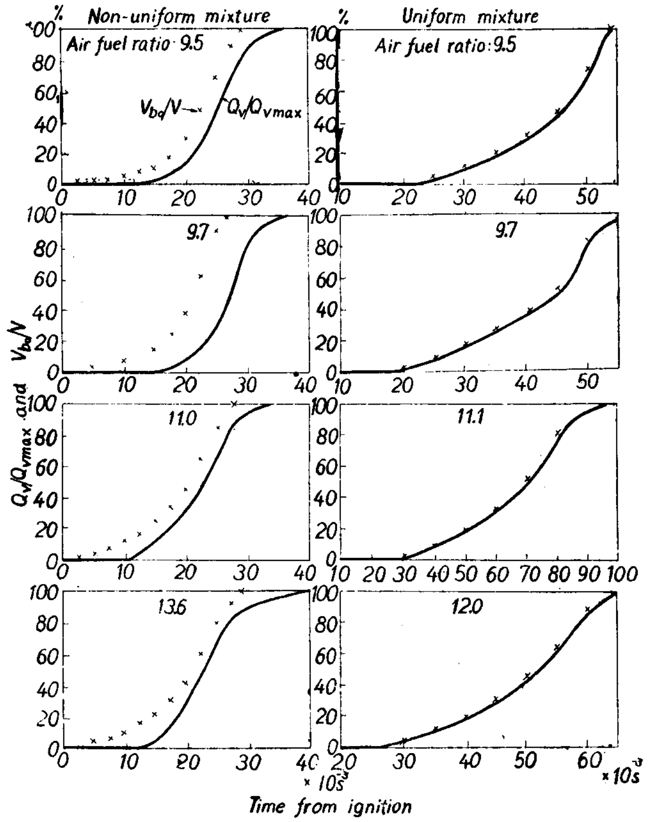


Fig. 19 Extent of combustion in non-uniform and uniform air-fuel mixture

Initial air-temperature: 120°C
Initial air-pressure: atmosphere
Ignition timing: $(56 \pm 6) \times 10^{-3}$s and five minutes after injection

*Comparison of combustion for early and delayed ignition.* The combustion properties were investigated for various charging quantities of gasoline, keeping the temperature and pressure constant. The mixture was ignited with a spark both a few hundredth of a second (early ignition) and five minutes (delayed ignition) after the start of injection. The five minutes interval between injection and ignition should permit the gasoline vapour to distribute uniformly, however for the ignition at a short time after injection the explosion takes place in the non-uniformly distributed mixture. In Fig. 19, the process of

$V_{b0}/V$ and $Q_v/Q_{vmax}$ for various mixture ratios is shown. For the explosion in uniform mixture, the curves drawn through the set of points of $V_{b0}/V$ follow essentially the same courses of $Q_v/Q_{vmax}$ whereas for the explosion in non-uniform mixture these two curves do not match. This fact suggests that the major portion of combustion in the uniform mixture is nearly completed as soon as the flame front has passed, whereas the combustion in the non-uniform mixture continues for a considerably long time after the charge is inflamed.

Now, in order to present a simple numerical relation between the flame development and the heat evolution, $Q_v/Q_{vmax}$ has been plotted against $V_{b0}/V$ in Fig. 20. The straight line on the digagram shows the total heat energy of the mixture included in the given inflamed volume at any instant during the combustion. If, therefore, the explosion completes at the flame front as in the uniform mixture, it indicates the relation between $Q_v/Q_{vmax}$ and $V_{b0}/V$. The data obtained here, however, do not follow the straight line: i. e., the process of heat evolution is very slow at the initial stage of combustion. This difference indicates the unburned energy included in the inflamed charge. The quantity of this unburned energy is small at the neighbourhood of the mixture ratio which gives the minimum combustion interval.

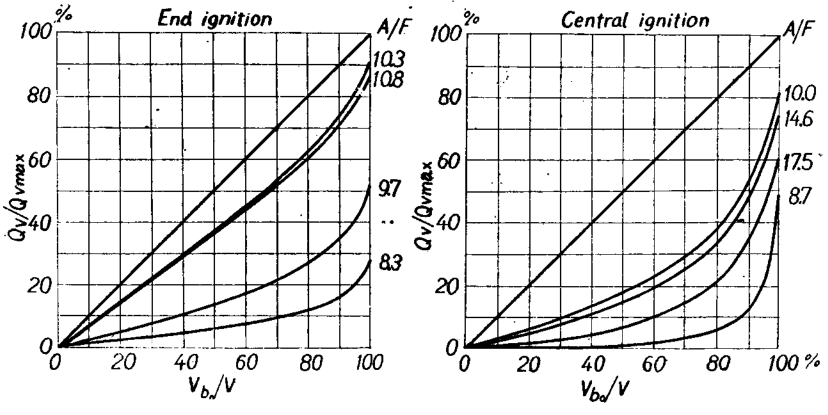


Fig. 20 Relation between $Q_v/Q_{vmax}$ and $V_{b0}/V$ as affected by air-fuel ratio

Initial air-temperature: 120°C
Initial air-pressure: atmosphere
Ignition: $(56\pm6)\times10^{-3}$s after injection

Initial temperature: 115°C
Initial pressure; atmosphere
Ignition: $60\times10^{-3}$s after injection

*Effect of spark timing.* The relation between $Q_v/Q_{vmax}$ and $V_{b0}/V$ is shown in Fig. 21, when the time interval elapsing between the start of injection and ignition is varied. The unburned energy decreases as the spark is delayed, because the mixing of fuel and air becomes good.

On the diagram, the effect of fuel volatility is indicated. The unburned energy in the inflamed charge decreases with higher volatile fuel, because the more volatile the fuel, the larger the velocity of vaporization.

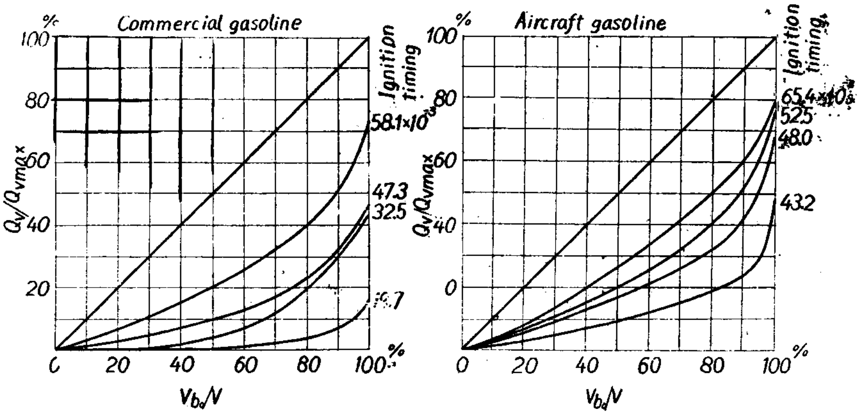


Fig. 21 Relation between $Q_v/Q_{vmax}$ and $V_{b0}/V$ as affected by ignition timing

Air-fuel ratio: 10:1
Initial air-temperature: 120°C
Initial air-pressure: atmosphere

*Effect of initial temperature of air.* Fig. 22 shows the effect of temperature. It is noted that the unburned energy decreases as the temperature becomes high.

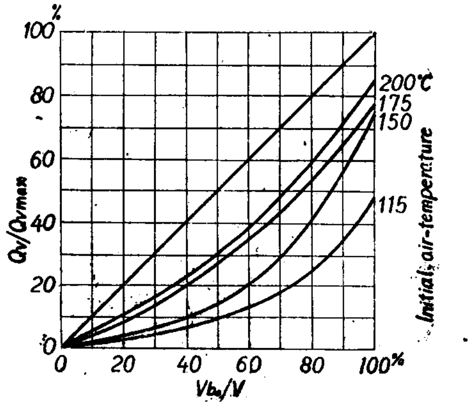


Fig. 22 Relation between $Q_v/Q_{vmax}$ and $V_{b0}/V$ as affected by initial air-temperature

Air-fuel ratio: 10:1
Initial air-pressure: atmosphere
Ignition: $48\times10^{-3}$s

## Summary

The test results may be summarized as follows:

(1) When gasoline is injected into the air of high temperature, the velocity of vaporization increases with an elevation of air temperature up to 200°C, however it remains almost constant above 200°C.

(2) For the combustion with early ignition, the maximum combustion pressure increases with the increase of the charging quantity.

(3) The progress of combustion, in general, can be divided roughly into five periods: An initial slow burning period, an accelerating period, a period of stationary rate of combustion, a period of rapid combustion and a period of after-burning. The whole combustion interval is controlled by initial combustion period.

(4) When the maximum rate of combustion is greater than $12\times10^4$ kcal/kg/s, knocking occurs.

(5) With later ignition, the longer the interval of the first period, the more rapid the combustion of end mixture. Therefore the increase of $(dQ/dt)_{max}$ and maximum pressure result.

(6) Injection pressure has no considerable effect. The ignition, however, is more reliable at higher injection pressure.

(7) Earlier ignition is reliable with the spark plug located nearer to the injector, however the range of the reliable ignition timing is reduced.

(8) For the combustion of uniform gasoline-air mixture, the major portion of combustion is nearly completed as soon as the flame front has passed, whereas the combustion in the non-uniform mixture continues for a considerably long time after combustion flame traverses the mixture.

(9) For the combustion of non-uniform mixture, the time interval required for complete heat release decreases and the behavior of the mixture approaches that of the uniform one, as the temperature is elevated.

## Reference

1) For the gasoline spray it had not yet been clarified. The data indicated in Fig. 2 were estimated, applying the test results using Diesel oil. cf. Sass: Kompressorlose Dieselmaschinen, (1929).

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