A Statistical Investigation of Ignition in a Fuel Spray Using a Shock Tube*

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In order to determine the general aspect of the spontaneous ignition in a fuel spray injected in compressed air at high temperature, which takes place usually in diesel and pulse jet engines, an experimental method using a shock tube is developed. A shock wave driven by high-pressure He gas propagates in the air in the low-pressure tube and reflects at a shock tube end. Through application of the pressure of the shock wave at reflection, *n*-octane fuel is injected into the air behind reflected shock waves in the shock tube. The fuel injection space is optically separated into 5 regions in the vertical direction, and the induction period of spontaneous ignition in each region is separately observed. As the induction period fluctuates markedly, the measured results are treated statistically and analyzed on the basis of the stochastic ignition theory.

Key Words: Liquid Fuel, Fuel Injection, Ignition, Shock Tube, Induction Period, Ignition Probability

1. Introduction

The combustion system of a liquid fuel spray injected into compressed high-temperature air is applied very often to Diesel engines as well as jet engines and has been well investigated. There are, however, still many problems in it to be cleared up for practical application.

As the experiments on spray combustion using a commercial engine have many difficulties because of its complicated structures, some apparatuses of adiabatic compression have been developed. A shock tube in which air is compressed and heated by shock waves can also be applied to the investigation.

Mizutani et al.⁽¹⁾ reported experimental results in which a spray consisting of many liquid fuel particles having almost the same size produced by an ultrasonic injector was injected into the air in front of the incident shock waves and ignited by the reflected shock

waves. In this case, however, a rapid evaporation of the fuel and mixing with the air proceeded in the rapid flow behind the incident shock waves; this phenomenon is almost the same as the ignition in a premixed mixture and quite different from the spray ignition.

Tsuboi et al.⁽²⁾ examined the combustion of fuel spray injected through an electromagnetic valve into the air behind reflected shock waves in a shock tube, but investigated only the production of soot by measuring the thermal radiation and no ignition.

The ignition delay in a fuel spray has been investigated by Mizutani et al.⁽¹⁾, Gyakushi and Takamoto⁽³⁾ using a direct-injection Diesel engine, by Ikegami et al.⁽⁴⁾ using a rapid compression machine and by Onuma and Higuchi⁽⁵⁾ using an electric oven, but in all cases only the average ignition delay has been investigated.

In this study, we want to investigate the ignition and combustion mechanism in a liquid fuel injected into the air behind reflected shock waves in a shock tube according to the stochastic ignition theory developed by Terao⁽⁶⁾. For this purpose, a fuel injector applying the shock waves and apparatus for measuring the induction period and position of ignition are developed. In this paper the experimental apparatuses and method are reported.

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2. Stochastic Ignition Theory

In the irreversible process the phenomena proceed in a nonequilibrium state and heterogeneously. Consequently they always show some fluctuations governed by a certain probability⁽⁶⁾. The electrical discharge and fracture of materials are typical irreversible phenomena. Zuber⁽⁷⁾ statistically studied the delay period of an electrical discharge based on the stochastic theory, while Hirata⁽⁸⁾ investigated the development of cracks produced on a glass plate at its fracture under a stress with a stochastic concept. From the results they concluded that fluctuations occur not because of the uncertainty of the experimental conditions, but from the character of the phenomena and express their essential mechanisms. Combustion phenomena are also distinctly irreversible processes just like electrical discharge and fracture. In the photographs of spontaneous ignition in some mixtures compressed in an adiabatic compression machine presented by Martinengo⁽⁹⁾, we observe that the ignition never takes place throughout the whole region of the mixture at the same time, even if the mixture state, temperature and density distributions in the mixture are homogeneous; i.e., the mixture has everywhere the same specific entropy, but starts only from a few points. Moreover, the ignition points as well as induction period of ignition are never constant, but fluctuate within a wide range.

Yamamoto and Terao⁽¹⁰⁾ measured the temperature of charged particles in a flame propagating in a propane-oxygen mixture using a laser light scattering method and observed ions and free electrons having a temperature much higher than the adiabatic combustion temperature. The mixture shows a mosaiclike pattern of varying high and low temperatures.

Thus, the characters of the irreversible process, the fluctuating phenomena and nonequilibrium state are also experimentally proved. The combustion is a distinctly irreversible phenomenon accompanied by some fluctuations. The stochastic ignition theory proposed by Terao has been applied to the investigations of ignition in Diesel engines^{(11),(12)}, hydrogen-oxygen mixture⁽¹³⁾, hydrocarbon-air mixture⁽¹⁴⁾⁻⁽¹⁸⁾ and spark ignition^{(19),(20)}.

According to the stochastic ignition theory,

- 1) the ignition is governed by a certain probability defined by the mixture state and
- 2) the ignition probability, therefore, can be obtained from the fluctuation of the ignition in time as well as in space.

The induction period t of ignition fluctuates within a wide range and never has a constant value, as schematically shown in a diagram of probability den-

Fig. 1 Ignition model

sity $q(t)$ in Fig. 1.

Assuming as follows:

$q(t)$: probability density of ignition

$P(t)$: probability of ignition whose induction period is longer than t

$\mu(t)$: probability of ignition per unit time in one mole mixture,

we obtain the equations^{(6),(8)}

$$P(t) = \int_t^{\infty} q(t) dt \quad (1)$$

$$\mu(t)P(t)dt = -dP \quad (2)$$

$$\mu(t) = -d \ln P / dt. \quad (3)$$

The ignition takes place through three steps, namely (1) initiation reaction, (2) development of the reaction to a certain critical size from which the reaction enlarges by itself and (3) enlargement of the reaction to the size which can be observed by the measurement apparatus. As the histogram or $\ln P(t)$ - t diagram of the ignition in Fig. 1 shows, the third step is the period τ in which no ignition is observed. This τ is reciprocally proportional to the reaction velocity. The average induction period t_m of ignition is, thus, expressed with the following equation:

$$t_m = \tau + 1/(m\mu) \quad (4)$$

where m is mole number of the mixture in the reaction state.

Repeating the same experiment many times, a histogram of the ignition induction period is obtained, from which further probability density $q(t)$, consequently $P(t)$ and the ignition probability $\mu(t)$ are obtained according to the equations (1), (2) and (3).

3. Experimental Apparatus and Method

The shock tube of stainless steel used in our experiment is schematically illustrated in Fig. 2. The shock tube has an outer diameter of 60 mm and inner diameter of 50 mm. The high-pressure tube has a length of 4 m, and the low-pressure tube, 7.54 m. The high-pressure tube is filled with He gas at an arbitrary pressure higher than 2.0 MPa, while the low-pressure tube is filled with air having an arbitrary pressure between 45 and 70 kPa. The gases are separated by a polyester film inserted between the high-pressure and low-pressure tubes.

Breaking the polyester film by a cutter at an

Fig. 2 Shock tube used in the experiment

Fig. 3 Shock diagram

arbitrary pressure ratio between the two gases, a shock wave propagates in the low-pressure air and reflects at the tube end. An example of the shock diagrams is shown in Fig. 3. The propagation velocity of the incident shock is detected by three piezoelectric pressure transducers set in the low-pressure tube at an interval distance of 1 750 mm between them. From the propagation velocity of the incident shock wave and the initial state of the air, the state of the air behind the reflected shock wave is estimated. At the shock tube end, the apparatus for fuel injection and that for ignition observation, as shown in Fig. 4, are attached. Upon reflection, the shock wave pushes a Plexiglas piston set at the tube end. The piston has a steel plunger at its backside, which compresses the liquid fuel *n*-octane ($n\text{-C}_8\text{H}_{18}$) and injects it through a nozzle set at a position 54 mm from the tube end into the air heated behind the reflected shock wave, perpendicularly to the tube axis. A pintle nozzle having an inner diameter of 1 mm and injection angle of 0° or 30° (NP-DN 0 SD 2110 and NP-DN 30 SDN 180, ZEX-ELL) is applied. Injection pressure of the nozzle is set at 12 MPa and injection starts 0.9 ms after the reflection of the incident shock wave, while the duration of injection is 0.9 ms and fuel quantity at each injection is 3 mg. Observing the variation of the secondary current through a solenoid wound around a permanent magnet set above the nozzle, the fuel injection time is measured.

As Fig. 5 shows, the ignition is detected through three photomultipliers, P_1 , P_2 and P_3 , set at both sides

Fig. 4 Fuel injection apparatus

Fig. 5 Photomultiplier arrangement for optical measurement of ignition

of the tube end. P_1 detects the luminescence in the upper part having a width of 20 mm, P_2 that in the middle part of 30 mm and P_3 that in the bottom part of 20 mm. Using these three photomultipliers simultaneously, we can optically separate the tube vertically into 5 sections having the same width of 10 mm and observe when and in which section the first ignition occurs. Photomultiplier P_4 can detect the ignition at the exit of the nozzle where other photomultipliers cannot detect it. The ignition in this area is only 4% of the whole ignition. Figure 6 shows an example of the oscillograms of ignition luminescence detected by the photomultipliers (931 A, Hamamatsu Photonics, observable wavelength: from 300 to 650 nm). P_1 , P_2 , and P_3 in the oscillogram mean the light power detected by each photomultiplier, respectively. For example, in Fig. 6(a) the ignition is observed first by P_3 , and then P_2 and P_1 . From the results we can recognize that the ignition takes place in the lowest region, 5. In Fig. 6(b) we observe the ignition by P_2 and P_3 simultaneously. This means that the ignition occurs in region 4.

As the induction period t of ignition, we take the period from the start of fuel injection to the instant at which the first ignition is observed by one or two photomultipliers. Under the same condition we repeat

(a): ignition takes place in section 5

(b): ignition takes place in section 4

Fig. 6 Oscillograms of ignition luminescence observed by photomultipliers

the experiment many times and obtain its histograms.

4. Experimental Results and Discussion

4.1 Measurement errors caused by experimental conditions and apparatus

In order to examine the influences on the ignition probability by the temperature and density of the compressed air and injection angle, we carry out the experiments under the following conditions.

In (I) and (II) the air behind reflected shock has the same density, but different temperatures, while in (I) and (III) it has almost the same temperature, but different densities. In the experiments from (I) to

No.	Temperature K	Pressure MPa	Density kg/m ³	Injection angle
(I)	1013	1.73	5.95	0°
(II)	1153	1.97	5.95	0°
(III)	1004	2.10	7.36	0°
(IV)	1270	1.52	4.17	30°

(III) the injection nozzle having the injection angle 0° is used, but in (IV) that of 30° is employed. In (I), (II) and (III), each experiment is repeated about 100 times; in (IV) about 200 times.

For the statistical investigation the reproducibility of the experiment is very important. Table 1 shown next suggests that the error of our experiments is small enough for this purpose.

Table 1 Experiment error

Fluctuation range of Mach number of the incident shock taken into account	Temperature range	Percentage of the experiment observed within the fluctuation range
±1.5%	±15.0K	91%
±1.0%	±10.0K	79%
±0.05%	± 5.0K	39%
±0.025%	± 2.5K	21%
±0.01%	± 1.0K	3%

Fig. 7 Fuel injection pressure

We take into account the measured results whose error is less than ±1.0%, as the error of the ignition probability caused by it is sufficiently small to disregard.

Figure 7 shows the fluctuation of the fuel injection pressure. Under condition (IV) the experiment is repeated 15 times and the injection pressure is measured every time by a piezoelectric pressure transducer. Overlapping all of the pressure variations, the pattern shown in Fig. 7 is obtained. The hatched area represents the fluctuation and suggests that the fluctuation of the injection pressure is so small that we do not need to consider it. We estimate from this result that the fluctuation of the quantity of injected fuel is within 2.5%.

4.2 Ignition probability

Figure 8 shows the histogram of the induction period of ignition observed in the whole region of the fuel spray in experiment (I). From such a histogram, probability density $q(t)$ can be obtained and further $P(t)$ according to Eq. (1), as shown in Fig. 9. From the curve of $P(t)$ we can further estimate the variation of the ignition probability according to Eq. (3). Using the same method, the ignition probability μ in experiments (II), (III) and (IV) can be obtained, as illustrated in Fig. 10.

In Table 2 the mean ignition induction period under each condition is also shown.

4.3 Variation of the ignition probability

In general, in a liquid fuel spray injected into high-temperature gas, the distributions of temperature and

Fig. 8 Histogram of ignition induction period

Fig. 9 $\ln(P) - t$ diagram

fuel concentration are heterogeneous in time and space. The ignition delay in a certain position consists of three periods, namely, a period in which some fuel droplets or vapor arrives at the position, a period in which a combustible mixture is formed by vaporizing and mixing of the fuel with air, and a period in which spontaneous ignition takes place in the mixture. The ignition probability depends also on the temperature and fuel concentration of the mixture at the position. In such a heterogeneous space the ignition delay is defined by the shortest one occurring at the position, while the overall ignition probability is obtained by integrating the local ignition probability throughout the entire space.

Based on these concepts, we discuss the influences of the temperature and density of the air and injection angle according to the ignition probabilities shown in Fig. 10, which were experimentally obtained under 4 different conditions described in section 4.1.

4.3.1 Influence of the air temperature As Fig. 10 shows, the ignition probability μ in every case reaches a finite value after a certain minimum induction period τ having an ignition probability of zero. The minimum induction τ and the ignition probability μ under the same air density and different temperatures of 1013 K and 1153 K are different from each other.

In experiment (I) at 1013 K, μ slowly increases

Table 2 The mean ignition induction period under each condition

Experiment	(I)	(II)	(III)	(IV)
Mean induction period of ignition	1.73 ms	0.82 ms	1.50 ms	1.05 ms

Fig. 10 Variations of the ignition probability in experiments (I), (II), (III) and (IV)

from the instant of 1.0 ms after the start of fuel injection until 1.5 ms, maintaining a low value, then increases rapidly. The fluctuation range of the ignition is relatively wide, from 1.0 ms to 2.4 ms after the injection start. In experiment (II) at a higher temperature of 1153 K the minimum induction period τ has a smaller value of 0.5 ms, and the ignition probability μ increases rapidly after this, until 1.0 ms after the fuel injection start.

As the fuel injection and the air density in these two experiments have the same condition, the period in which the fuel droplets or vapor reaches the measuring points should be almost the same. The discrepancy of μ variation should therefore be caused by the difference of the velocity of fuel vaporization and that of temperature of the combustible mixture formed during the injection. Such a temperature dependence of τ and μ is also observed at the spontaneous ignition in hydrocarbon-air mixtures.

4.3.2 Influence of the air density We compare the results in experiments (I) and (III) carried out under the same temperature but different densities. By increasing the air density, the spray length should be shortened and the heat capacity of the air increases; namely, the mixture volume around the fuel spray decreases, while the heat capacity of unit volume air increases and accelerates the vaporization of the fuel droplets. The two phenomena have opposite effects upon each other. In both experiments (I) and (III) almost the same minimum induction period of 1.0 ms is observed, but the ignition probability μ in (III) has a larger value and the fluctuation range is much smaller. This suggests that both the effects

Fig. 11 Spatial distribution of the ignition

described above work against one another during the first step of fuel injection which defines the minimum induction period, while the heat capacity of the air exerts a greater effect afterwards.

4. 3. 3 Influence of the injection angle In experiment (IV), having an injection of angle 30° , a short minimum ignition induction period τ is observed, but the ignition probability μ cannot increase at once after this period; namely, it maintains a small value for a time and then increases rapidly to a maximum value. This occurs for the same reason as in (II). In the case of (IV) having a large injection angle, the velocity of injected fuel droplets is so small that the fuel stays in the upper part and vaporizes there, decreasing the air temperature. In addition, the air density is also small. Therefore, the ignition probability first shows a small value. With time, however, the fuel spray expands, mixing proceeds and the mixture temperature increases, too. Thus, the ignition probability increases rapidly, and reaches a larger maximum value. Such a phenomenon, in which the ignition is delayed by increasing the fuel quantity injected into air of unit volume, was also observed by Ishii et al.⁽²¹⁾.

4. 4 Spatial distribution of ignition

As the ignition in the five sections is optically observed separately, we can have a spatial distribution of ignition, as shown in Fig. 11. Here, (a), (b), (c) and (d) correspond to (I), (II), (III) and (IV).

4. 4. 1 Influence of the air temperature

Comparing the results in Figs. 11(a) and (b), we observe a remarkable difference of ignition position at the different temperatures but the same density. In the experiment (I) of lower temperature, the ignition is scarcely observed near the injection nozzle, but increases with axial distance from the nozzle. In the experiment (II) of higher temperature, the frequency of ignition has a maximum in the middle region and is very low in the lowest section.

In experiment (I), the ignition probability depending on temperature has a small value in the upper sections 1 and 2 where the air temperature decreases

with the vaporization of fuel, while in experiment (II) a mixture having a high ignition probability is formed near the nozzle just after the injection start, as the air temperature is high enough for it and the mixing area spreads with the fuel injection. Moreover, in experiment (I), the injected fuel droplets sometimes reach the bottom of the tube and therefore the ignition takes place in the lowest section most frequently. This result suggests also that our conclusion described in section 4. 3. 1. is correct.

4. 4. 2 Influence of the air density In order to observe the influence of the air density, we compare the distribution of ignition frequency shown in Figs. 11(a) and (c) corresponding to the experiments (I) and (III). As described in sections 4. 4. 1 and 4. 3. 2, the ignition frequency has a maximum value at the top of the spray in the air of lower density, as shown in Fig. 11(a), while the maximum ignition frequency is observed near the injection nozzle in the experiment (III) of high air density because of the effects of heat capacity and spray length, as shown in Fig. 11(c).

4. 4. 3 Influence of the injection angle At the narrow injection angle, the ignition frequency increases with the penetration of the fuel spray to the downstream direction, while it has an inverse tendency at the wide injection angle. At a wide injection angle, the ignition frequency shows a maximum value near the nozzle in the upper section and is almost zero in the lowest sections 4, and 5. This is caused by the spray length.

As above explained, using the ignition probability for the entire spray space as well as those in different parts of the spray, we can observe the temporal and spatial variations of ignition in a fuel spray. From the ignition frequency for the whole space and that in each small section, we can calculate the ignition probability in each section. Using such a distribution of the ignition probability, we can investigate the ignition mechanism in a fuel spray more exactly. As the mixture part having a high ignition probability is ignitable, from the distribution of ignition probability

we can estimate the lane of the flame propagation.

From the ignition probability in each position, we can also find out the region where the flame most rapidly propagates.

Ignition probability in each section and its analysis at the wide injection angle will be reported in our next paper.

5. Conclusions

Using a shock tube, the spontaneous ignition in a fuel spray is statistically investigated, and from the results we conclude as follows:

1. In the experimental investigation of the spontaneous ignition in a liquid fuel spray injected into the air behind the reflected shock wave in a shock tube, a stable and reproducible injection can be carried out applying the shock wave. Arranging several photomultipliers around the shock tube, the induction period and position of the ignition can be measured. By this method the ignition is statistically investigated.

2. Applying the stochastic ignition theory, the temporal and spatial variation of the ignition can be qualitatively investigated, and its mechanism is explained more exactly than by the method using the mean ignition induction period.

3. Applying the stochastic ignition theory, the temporal and spatial distribution of the ignition probability in a fuel spray can be obtained. Comparing these results with the ignition probability in the homogeneous mixture of the same fuel and visualized spray form, we can expect to analyze the ignition mechanism and make assumptions regarding the flame propagation lane after the ignition.

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