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Electrostatic Probe Measurements in Propagating Flames*

(Part 1, The Relation between Flame Front Configuration and Ion Current)

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An experimental study has been made for ascertaining the relation between the combustion phenomena of a propagating flame and the ion current from the flame to an electrostatic probe or ionization gap. A schlieren system was simultaneously used together with the electrostatic probe to study a flame propagating through a stoichiometric propane-air mixture in a closed combustion tube in the initial pressure range from 100 to 600 mm Hg. It was found that the flame front might be disturbed by the turbulence of the unburned gas flow. The measured distance between the locations of schlieren front and maximum ion current lay in the range from 2 to 6 mm. When the flame front was disturbed, the ion current fluctuations were observed. These ion current fluctuations were superimposed on the ion current indicating the passing of the flame front and were inferred to be closely related to the flame front configuration.

1. Introduction

It is well known that near the reaction zone of a premixed or diffusion hydrocarbon-oxidizer including oxygen flame, a region exists where the ion density of the gas is enormously high as compared to that predicted on the assumption of thermal equilibrium ^{(1)~(4)}.

The ions in this region are considered to originate mainly from chemi-ionization, and the most acceptable scheme for the production of primary ions is ⁽¹⁾⁽²⁾⁽⁴⁾

or

Various reactions involving these primary ions by which secondary ions and finally H_3O^+ are produced have been explored.

Since these ions originating from chemi-ionization decrease rapidly by recombination, the high ion density is confined in a narrow region near a flame reaction zone. Based on this fact, an electrostatic probe or ionization gap has been used for measuring the flame propagation velocity in an internal combustion engine or tube ^{(4)~(6)}, or for detecting the

flame front of a turbulent or vibrating flame ⁽⁴⁾⁽⁷⁾⁽⁸⁾. In these cases, the electrostatic probe or ionization gap has been used as a means by which the passing of a flame front is recorded. However, the ions near the flame reaction zone originate from chemical reactions, so that a quantitative relation between the fuel quality or combustion phenomena and the generated ion density can be established. Iinuma ⁽⁹⁾, Hamamoto ⁽¹⁰⁾, and Ohigashi et al. ⁽¹¹⁾ have tried to elucidate the relation between the combustion phenomena in an internal combustion engine and the ion current to an ionization gap. In these studies, several aspects have been elucidated. At the same time, many problems have been pointed out. Indeed, many subjects which are needed for establishing the relation between the combustion phenomena and the ion current remain in a state of ambiguity as yet, such as the distance between the front near the flame reaction zone detected using an electrostatic probe or ionization gap and one observed on a schlieren photograph, the relation between the ion current and flame front configuration, etc.

In this study, in order to obtain a basic knowledge of the relation between the combustion phenomena and the ion current, flames propagating through stoichiometric propane-air mixtures in a closed combustion tube in the initial pressure range from 100 to 600 mm Hg were measured simultaneously using electrostatic probes and schlieren photography. The distances between the detected fronts using these two methods were examined. Furthermore, the aspects of propagating flames were compared with the corresponding ion current records.

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2. Experimental apparatus and procedure

2.1 Combustion tube

In a study of propagating flames in a closed combustion chamber, the dimensions of the chamber have been determined such as to suit the purpose of the study. In the present fundamental experiment of propagating flames, a combustion tube of 3 x 3 cm cross section and 100 cm long was prepared (Fig. 1). At one end of the combustion tube, an ignition system was placed, and at the other end, a pressure transducer was placed. Side walls near the midpoint of the combustion tube were optical quartz plates of 3 x 10 cm area and 1 cm thick for taking schlieren photographs.

Propane was fed from a cylinder through a pressure regulator and a control valve to a mixing chamber. Air from a drier was compressed using a compressor and fed through a pressure regulator and a control valve to the mixing chamber. The cylindrical mixing chamber of 40 cm in diameter and 60 cm high has a mixing system which consists of a magnetic field generator outside the mixing chamber and magnetically rotating blades inside the mixing chamber.

At the beginning, the mixing chamber was filled with air, which had passed through the drier, of room temperature and of atmospheric pressure p_0 . Subsequently,

propane was gradually fed to the mixing chamber and the pressure was increased to p_a . Again, air was gradually fed to the mixture and the pressure was increased to p_b . p_a and p_b were measured with mercury-column manometers. The mixture ratio was controlled by selecting appropriate values of p_a and p_b . The propane and air fed to the mixing chamber were mixed with the mixing system. The homogeneity of the mixture depends on the duration of the mixing. The mixtures of various mixing times were analyzed using a gas chromatograph, and the variation of the scattering range of the measured mixture ratios ϕ , represented by the equivalence ratios, with mixing time is shown in Fig. 2. By mixing for more than 6 hours, the scattering range of the measured mixture ratios becomes narrow, indicating that the homogeneity of the mixture becomes better. In the present experiment, the gases were mixed well for more than 24 hours. In this case, the deviation of the mixture ratio from its mean is less than $\pm 1.5\%$.

To examine whether the mixture separation into its components occurs during the period from the filling of the mixture in the combustion tube to the ignition or not, the mixture ratios ϕ at various times from the filling were examined. The result indicated that no detectable separation of the mixture into its components occurred even at the time of more than 15 minutes after filling of the mixture.

It is well known that the behavior of a propagating flame is strongly influenced by the turbulence existing in the unignited mixture (1) (2). Under the conditions covered by the present experiment, the flame propagation velocity and the behavior of the propagating flame were confirmed to change scarcely if the mixture was ignited after 2 minutes had passed from the time of the filling of the mixture to the combustion tube. Therefore, the mixture was ignited when 5 minutes had passed after filling of the mixture.

In general, an electric spark or heated wire is used for igniting the mixture. The ignition with an electric spark yields a small variation of the ignition time but causes an electrical noise which disturbs electrical measurements. On the contrary, the ignition with a heated wire yields a large variation of the ignition time but scarcely causes an electrical noise. Therefore, the ignition with a heated wire might be suitable for the present experiment in which the electrostatic probe measurement was made, so that a heated nichrome wire was used for igniting.

A mini-transistor pressure transducer with piezo resistor effect was used for the pressure measurement in the combustion tube. The diameter of the detecting element was 5 mm. This pressure transducer could normally operate in the pressure range from 0 to 20 kg/cm. The result of the calibration in the pressure range of the present experiment showed that the

Fig. 1 Experimental apparatus

Fig. 2 Variation of the homogeneity of the mixture with mixing time

errors were within $\pm 1\%$. Furthermore, this pressure transducer was stable against the temperature change, and the errors were confirmed to be within $\pm 1\%$ in the temperature range from -30 to $+60^\circ\text{C}$. During the flame propagation through the combustion tube, the gas temperature would rise due to the pressure increase and combustion. However, the pressure transducer was placed at the tube end where the temperature was always below 60°C , so that the temperature was considered to be kept below 60°C due to the heat transfer to the wall until the flame reached the tube end. When the flame reached the tube end, the gas temperature near the detecting element of the pressure transducer would become so high that the temperature of the detecting element would be transiently beyond 60°C . At this moment, the pressure transducer might not indicate a real value. In the pressure measurement, a sudden change of the value indicated by the pressure transducer was observed at the time when the flame was supposed to reach the detecting element.

2.2 Electrostatic probe

The structure of the electrostatic probe used in the present experiment is shown in Fig. 3. 0.1 mm diameter probe wires were of platinum. Since probes of platinum are electrically conductive and are hardly oxidized in high temperature gases, they have been usually used in flames or in combustion gases. Although the length and location of the exposed detecting part of the probe wire could be changed, the detecting part was determined to be 2 mm long and located at the center of the tube cross section. Except for the

① Platinum wire, 0.1 mm ③ Quartz tube
② Detecting part ④ Combustion tube wall

Fig. 3 Electrostatic probe system

Fig. 4 Current-voltage characteristics of single and double probes

detecting part the wire was covered with a quartz tube of 1 mm diameter. The probe potential with respect to the combustion tube, being earthed, was kept constant (-20 V), and the ion current to the probe was recorded with an oscilloscope.

The ion current to the probe depends on the phenomena near the cathode $(3) \sim (7)$, so that there may be no difference between the ion currents to the probe (single probe) and to the ionization gap (double probe) usually used in the internal combustion engine if the distance between the detecting parts of the ionization gap is not so small. To make sure of this fact, the characteristics of the electrostatic probe used in the present experiment and of the double probe were examined experimentally and compared to each other. The length of the two identical detecting parts of the double probe was equal to that of the single probe and the distance between the detecting parts were 1.5 mm. A typical result is shown in Fig. 4, where the probe potential is varied from -5 to -100 V. A difference between the two characteristics is scarcely observed. In the present experiment, the electrostatic probes were placed at 9 points of the combustion tube and used for the measurement of the propagating flames (Fig. 1).

2.3 Schlieren system

To take the schlieren photographs a stroboscope covered by a plate with 1.5 mm diameter hole was used as a light source. The duration of its flash was 30 μ sec. The focal lengths of the two concave mirrors of 200 mm diameter were 2015 and 2025 mm. The knife edge was placed at the point where the image of the light source was formed, and its direction was so determined that density gradient in the direction of the flame propagation can be detected.

3. Flames propagating through the combustion tube

3.1 Flame propagation velocity

When a flame passed the detecting part of the electrostatic probe, the ion current increased very rapidly to a maximum and then decreased rapidly. In the propagating flame measurement using an electrostatic probe or ionization gap, the flame front was considered to pass the detecting part of the probe at the time when the maximum ion current was recorded. By simultaneously recording the ion currents to the electrostatic probes placed at two different points, the period from the time when the ion current to the first probe reached its maximum to the time when the ion current to the second probe reached its maximum could be measured. By dividing the distance between the two probes by this period the flame propagation velocity could be deduced. This period might be needed for the flame propagation between the two probes. Figure 5 shows the relation between the flame propagation velocity V_f and the ratio l/L of the distance l

from the ignition end to the flame front to the combustion tube length L at the initial pressure $p_i = 200, 300, \text{ and } 500$ mm Hg. V_f is almost constant throughout the combustion tube except for the locations near the tube ends. V_f became very large at the center of the tube cross section near the end where the heated wire was placed. However, the data were so scattered that they could not be plotted in Fig. 5. Near the other end, V_f decreased rapidly as the flame approached the end. The variations of V_f with l/L are similar for the cases of various p_i , and V_f increases with the increase of p_i .

3.2 Flame propagation and pressure change in the tube

As a flame propagated through the combustion tube, the pressure in the tube increased. In the present experiment, V_f was in the range from 2 to 8 m/sec, and the gas velocity in the tube might be small enough as compared to the velocity of sound. Therefore, the pressure p at a given instant might be independent of the location. Thus, the value recorded at the end with the pressure transducer must be equal to the pressure at the other locations. By simultaneously recording the ion current to the electrostatic probe and the signal from the pressure transducer placed at the tube end, the relation between the flame location and p was examined. The results are shown in Fig. 6. The

Fig. 5 Flame propagation velocity in the combustion tube

Fig. 6 Pressure change in the combustion tube

ratio of p to p_i , p/p_i increases with the increase of the distance l from the ignition end to the flame front, and at $l = 0.9L$, p/p_i is about 3. Furthermore, p/p_i at a given value of l/L is found to increase with the increase of p_i . This fact may be explained by considering that as V_f increases, the ratio of the heat loss to heat generation may decrease.

3.3 Initial pressure and flame front configuration

Schlieren photographs shown in Figs. 7(a)~(f) indicate typical flames propagating near the mid-point of the combustion tube from the left-hand side to the right-hand side at $p_i = 100 \sim 600$ mm Hg. At $p_i = 100$ mm Hg, the flame front is not disturbed (Fig. 7(a)). At $p_i = 200$ mm Hg, the flame front is found to be disturbed slightly (Fig. 7(b)). As p_i increases further, the scale of the flame front dis-

(a)
 $p_i = 100$ mm Hg

(b)
 $p_i = 200$ mm Hg

(c)
 $p_i = 300$ mm Hg

(d)
 $p_i = 400$ mm Hg

(e)
 $p_i = 500$ mm Hg

(f)
 $p_i = 600$ mm Hg

Fig. 7 Schlieren photographs of propagating flames

turbance becomes small and the intensity of disturbance increases (Figs. 7(c)~(f)).

The mixture was ignited after a long period from the filling of the mixture in the combustion tube, so that no residual turbulence in the mixture might exist at the ignition. However, the disturbed flame front could be observed at $p_i \geq 200$ mm Hg. Therefore, this flame front disturbance was reasonably inferred to be generated in the process of igniting or flame propagation.

If disturbance was generated in the process of ignition, the scale or intensity of the disturbance would depend on the method of igniting. However, in the present study as well as in other studies the aspect of flame front disturbance on a schlieren photograph was almost independent of the method of igniting.

In general, the flame front disturbance of a premixed flame is recognized to be closely related to the gas movement near the flame front. If the turbulence is generated in the process of flame propagation through a homogeneous mixture including no turbulence at the ignition, the interaction between the flame and the gas movement near the flame front caused by the flame propagation has to be taken into account. The flame front may be disturbed if the gas flow in the combustion tube is turbulent. The Reynolds number based on the tube diameter is a representative value which indicates the character of the flow in the combustion tube.

The gas movement can be estimated near the flame front. Since the laminar burning velocity S_u is a velocity component of the unburned mixture normal to the flame front (18), the mean gas velocity $\bar{V}_u$ of the unburned side of the flame front can be expressed as

$$\bar{V}_u = V_f - \frac{A_f}{A_t} S_u, \quad \dots (1)$$

where A_f and A_t represent the areas of the flame front and the tube cross section, respectively. Furthermore, the mean gas velocity $\bar{V}_b$ of the burned side of the

flame front can be expressed as

$$\bar{V}_b = V_f - \frac{A_f}{A_t} \frac{\rho_u}{\rho_b} S_u, \quad \dots (2)$$

where ρ_u and ρ_b represent the densities of the unburned mixture and burned gas, respectively.

Taking into account the variation of the kinematic viscosity with temperature, the Reynolds number at the unburned side could be estimated to be larger than that at the burned side. Therefore, to know the character of the flow in the combustion tube, the Reynolds number $Re_u = \bar{V}_u(d/\nu)$ at the unburned side was estimated, where d is the width of the tube wall. $\bar{V}_u$ was estimated using Eq. (1). A_f/A_t was determined by estimating the flame front area on the schlieren photograph. In the case of $p_i \leq 400$ mm Hg when the flame front disturbance was slight, the values of A_f/A_t ranged from 2.2 to 2.4 and were almost constant. For the cases of large values of p_i , flame fronts were strongly disturbed, so that the flame front area could hardly be determined. In these cases, A_f/A_t was assumed to be 2.3. The variation of Re_u near the mid-point of the combustion tube with p_i is shown in Fig. 8. At $p_i = 200$ mm Hg where the flame front began to be disturbed, Re_u is about 2200. This value is very near the critical Reynolds number of 2300 at which the transition from the laminar to the turbulent flow takes place in a tube. The flow field near the flame front will be different from that of the ordinary pipe flow, so that the critical Reynolds number will be somewhat different. However, from the above calculation the flame front disturbance can be inferred to be caused by the turbulence in the unburned gas flow.

4. Ion current variation and propagating flame

4.1 Locations of maximum ion current and schlieren front

The ion current variations recorded by the electrostatic probes are shown in Figs. 9(a)~(f). The corresponding schlieren photographs shown in Figs. 7(a)~(f) were taken at the same time. The ion current was recorded with the electrostatic probes A and B (Fig. 1). The distance between them was 4 cm, and the probe A was placed at the mid-point of the window. Of the two ion current variations recorded on one photograph, the top one is recorded with the probe A, and the bottom one is recorded with the probe B. The first maximum in the ion current variation may represent the passing of the flame. Since at the moment when the ion current to the probe A reached a maximum the light source of the schlieren photograph was set to flash, the location of the probe A could be considered to correspond to that of the maximum ion current to the probe A. From Figs. 7(a)~(f), it can be found that there is a distance Δx between the locations of the detecting part of the probe and the schlieren front of the flame.

Fig. 8 Variation of the Reynolds number at the unburned side of a propagating flame with initial pressure

The difference between the times at the maximum ion current and the flash was confirmed to be very small and less than 2×10^{-5} sec. Assuming a flame propagation velocity of 10 m/sec, the corresponding distance will be less than $2/10$ mm so that it is smaller than the error which will be caused in the measurement of the location. The relation between Δx and P_i is shown in Fig. 10. For various values of P_i , Δx ranged from 2 to 6 mm, which are rather large values.

4.2 Flame front configuration and ion current

In order to elucidate the extent to which the behavior of a propagating flame can be inferred from the ion current variation, the relation between the aspect of the schlieren front and the ion current variation was discussed. At $P_i = 100$ mm Hg, the schlieren front was not disturbed and only a single ion current maximum which represented the passing of the flame front was observed. At $P_i = 200$ mm Hg, the flame front disturbance could be found on the

schlieren front, while the effect of this disturbance on the ion current could not be observed. At $P_i = 300$ mm Hg, near the maximum which represented the passing of the flame front there appeared ion current fluctuations. As P_i increased further the number and the value of these ion current fluctuations increased, but even at $P_i = 600$ mm Hg, the values of the ion current fluctuations were much smaller than the largest ion current. As shown in Fig. 11, the maximum ion current increases with the increase of P_i .

If the ion current fluctuations corresponded to the ion density fluctuations near the detecting part of the electrostatic probe, they might represent the aspect of the turbulent flame front. In the case of $P_i = 200$ mm Hg, the schlieren front could be found to be disturbed, but since the scale of the disturbance was much larger than the dimension of the detecting part of the electrostatic probe, the effect of the disturbance on the ion current could not be observed. The ion current fluctuations appearing at $P_i = 300 \sim 600$ mm Hg

Fig. 9 Ion current variations

Fig. 10 Variation of the distance between the locations of the maximum ion current and schlieren front with initial pressure

Fig. 11 Variation of maximum ion current with initial pressure

might not represent the passing of the flame front because of their small values. It is reasonably inferred that the ion current fluctuations are caused by the ion density distribution change generated by the flame front curvature in the direction of the tube axis.

For $P_i \geq 400$ mm Hg, the ion current to the probe was recorded at 10~20 cm behind the flame front. The value of this ion current increased with the increase of P_i , and changed very rapidly. To explore this phenomenon, the ion current was recorded at low sweep speed (Fig. 12(a)~(d)). The ion current variations recorded by the probes A and B indicate that behind the flame front the high density region of ions moves in an opposed direction to the flame propagation. The high ion density region may move in the same direction as the combustion gas moves. The mechanism by which the ions were generated behind the flame front has not been elucidated as yet. To explore this phenomenon, the ion current variations should be recorded simultaneously with the schlieren photographs.

(a)

$P_i = 300$ mm Hg, Sweep: 5 msec/cm

(b)

$P_i = 400$ mm Hg, Sweep: 5 msec/cm

(c)

$P_i = 500$ mm Hg, Sweep: 5 msec/cm

(d)

$P_i = 600$ mm Hg, Sweep: 5 msec/cm

Fig. 12 Ion current variations (recorded at low sweep speed)

In the next stage this will be done, and presently the project of the experiment is being prepared. The results will be presented elsewhere.

From the above results, it is seen that the overall aspects of the flame front disturbance can be inferred using the schlieren photographs, but the local flame position or turbulence can be inferred from the ion current measurement to a greater extent.

5. Conclusions

Flames propagating through stoichiometric propane-air mixtures at various initial pressures in a closed combustion tube were measured simultaneously using electrostatic probes and schlieren photography, and the results were analyzed. Consequently, the following conclusions were obtained:

(1) The flame propagation velocity at a given value of the initial pressure is almost constant throughout the combustion tube except for the locations near the tube ends. The flame propagation velocity increases with the increase of the initial pressure.

(2) The ratio of the pressure at the time when a flame passes a given point in the combustion tube to the initial pressure increases with the increase of the initial pressure. This fact may be explained by considering that as the flame propagation velocity increases, the ratio of the heat loss to heat generation may decrease.

(3) The flame front disturbance is observed when the Reynolds number at the unburned side is larger than 2200, and it can be inferred to be caused by the turbulence in the unburned gas flow.

(4) In the initial pressure range from 100 to 600 mm Hg, the distances between the fronts of the maximum ion currents and on the schlieren photographs are found to range from 2 to 6 mm, which are rather large values.

(5) When the flame front is disturbed, the ion current fluctuations are observed. These ion current fluctuations are superimposed on the ion current indicating the passing of the flame front. As the initial pressure increases, the number and the value of these ion current fluctuations increase. These ion current fluctuations are inferred to be closely related to the disturbed flame front configuration.

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