A Study on the Structure of Premixed Turbulent Propagating Flames*

(An Investigation and Application of the Flame Plasma Potential Signal)

Hiroyuki KIDO**, Shuwei HUANG**
and Kenshiro NAKASHIMA**

A method using a passive electrostatic probe to detect a flame by its plasma potential signal has been developed. The spatial resolution of the probe in this method is shown to be significantly improved over that of the conventional electrostatic probe. The plasma potential signals obtained by this method from premixed turbulent propagating flames show one to six spikes in each signal; each spike is considered to be a flamelet in the flame zone. On the basis of this consideration, the propagating speed, the thickness of the flame zone, the number of flamelets in the zone, the separation distance between two adjacent flamelets, etc., of the flame, were obtained. The results of this experiment suggest the existence of "reactant islands" in the turbulent flame zone, and show that the number of flamelets in the zone increases with an increase in the turbulence intensity for the same mixture and/or a decrease in the Damköhler number for mixtures with the same turbulence intensity.

Key Words: Combustion Phenomenon, Premixed Combustion, Flame Plasma Potential, Electrostatic Probe, Turbulent Flame Structure

1. Introduction

The phenomenon that quantities of ions exist in the flamelets of hydrocarbon flames is often used to detect the flamelets using a probe supplied with a negative electric potential⁽¹⁾. Such a probe is called a Langmuir probe⁽²⁾ or an electrostatic probe⁽³⁾. The signals thus obtained can be called ion current signals. However, owing to the externally-supplied electric potential, there exists an ion sheath surrounding the probe, whose thickness depends on the electric potential supplied⁽⁴⁾, making it difficult to compare measurement results by different researchers. Moreover, as a flame has complicated electric properties, before it is detected, its structure may have been affected by the electric field around the probe. In order to overcome the above difficulties caused by the externally-supplied electric potential, an attempt was made to detect a flame using an electrostatic probe without any externally-supplied electric potential (i.e., a passive

probe). This was done in the case of premixed laminar flames in a constant-volume combustion chamber. It was found that one can obtain an electric potential signal from the flame by using such a probe. The signal was attributed to the plasma potential of the flame and was shown to be applicable to the detection of the flamelets of premixed turbulent flames. For convenience, the plasma potential signal of a flame is referred to as a flame potential signal. Accordingly, the method of detecting a flame by its flame potential signal is referred to as a flame potential method, and the method of detecting a flame by the ion current signal is referred to as an ion current method, which is the conventional method.

By comparing the flame potential signal with the ion current signal, it was shown that a probe working on the flame potential method has a higher spatial resolution than one working on the ion current method. Therefore, the flame potential method was applied to the investigation of the structure of premixed turbulent propagating flames. As a result, many important parameters concerning the flame structure, such as the thickness of the flame zone, the number of flamelets in the zone, the average separation distance

* Received 6 th July, 1990. Paper No. 89-0205B

** Faculty of Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812, Japan

Table 1 Properties of mixtures used

MIXTURE	COMPOSITION	S_L (m/s)	δ_L (mm)	ϕ	η (mm)	ν (m ² /s)	T_b (K)
43-P10-23	$C_3H_8 + 5O_2 + 17.06N_2 + 0.36He$	0.43	0.23	1.0	0.045	1.43×10^{-5}	2329
43-P10-31	$C_3H_8 + 5O_2 + 15.40N_2 + 5.60He$	0.43	0.31	1.0	0.071	1.76×10^{-5}	2262
73-P10-23	$C_3H_8 + 5O_2 + 10.50N_2 + 6.50He$	0.73	0.23	1.0	0.047	1.90×10^{-5}	2440

1-Fan ; 2-Window ; 3-Perforated plate ;
4-Electrostatic probe

Fig. 1 Combustion chamber

1-Ignition plug ; 2-Electrostatic probe ; 3-Combustion chamber ; 4-Insulator ; 5-Supporting tube

Fig. 2 Measurement circuits and electrostatic probe

between adjacent flamelets in the flame zone, and the flame propagation speed, were obtained.

In addition, the measured average thicknesses of flame zones were compared with the predicted ones obtained by a flame structure model proposed by the authors⁽⁵⁾.

2. Experimental Apparatus

2.1 Combustion chamber and mixtures

As shown in Fig.1, the combustion chamber⁽⁶⁾ used in this experiment was a constant-volume vessel having a spherical inner space, in which a steady and approximately isotropic turbulent flow field with the desired turbulence intensity was created. The ignition plug (omitted in the figure) was located at the center of the chamber. In order to obtain the flame potential signal, it is necessary to insulate all conductors except the sensor of the probe from the flame. Thus, the surface of the ignition plug as well as that of the supporting tube of the probe was insulated.

There were three propane/air (artificial) mixtures used in this experiment, whose compositions are given in Table 1, where S_L is the laminar burning velocity, δ_L is the thickness of the laminar flame reaction zone, ϕ is the equivalence ratio, η is the thickness of the preheat zone of the laminar flame, ν is the kinematic viscosity, and T_b is the constant-pressure adiabatic flame temperature of the mixture.

2.2 Measurement circuits

There were two circuits involved in this work, as

shown in Fig.2 : the one on the left-hand side without any electric potential supplied to the probe was used for the flame potential method, referred to as "circuit I"; the other on the right-hand side is a typical one for the ion current method, referred to as "circuit II" and was used to obtain the ion current signal as a reference for comparison. In the circuits, R_{in} ($=1M\Omega$) is the input impedance of the signal recording device ; R_1 and R_2 are variable resistances, adjusting the magnitudes of the input signals if necessary, usually set to infinity to increase the S/N ratio.

3. Examination of the Flame Potential Signal Using Laminar Flames

3.1 Comparison of the flame potential signal with the ion current signal

It is known that quantities of ions exist in the flamelets of hydrocarbon flames. When a flamelet passes through a probe that has been supplied with a negative electric potential, the positive ions in it are drawn up to the probe, resulting in a current signal in the measuring circuit ; this is the principle of the ion current method. However, the flame potential method works on a different principle. The probe in this method has not been supplied with any electric potential. When a flamelet passes through the probe in circuit I, the ions in it collide with the probe and transfer the charges they are carrying to the probe, resulting in a voltage signal at the sampling point m_1 in circuit I (see Fig. 2). When the number of positive

charges transferred to the probe is greater than that of the negative ones, the voltage obtained at m_1 is positive, or negative in the reverse case. As the motive force causing the ions to transfer their charges to the probe is attributed to the plasma potential of the flamelet, a signal thus obtained is regarded as the plasma potential signal of the flamelet (the flame potential signal).

In order to compare the flame potential signal with the ion current signal, two probes with the same size ($d_p=0.2$ mm, $L_p=0.6$ mm) were inserted into the combustion chamber through the window, as shown in Fig.1, where the two probes were the same distance away from the ignition plug (28 mm), which was located at the center of the combustion chamber. As shown in Fig. 2, of the two probes, one was connected to circuit I (where $R_1=\infty$) to obtain the flame potential signal and the other to circuit II (where $E=-190$ V, $R_2=\infty$) to obtain the ion current signal. When the static premixed mixture was ignited at the center of the combustion chamber, the laminar flame front propagated outwardly, remaining spherical and reaching the two probes at the same time. The two signals thus obtained are shown in Fig. 3, where signal m_1 is the flame potential signal obtained by circuit I at m_1 , and signal m_2 is the ion current signal by circuit II at m_2 (refer to Fig. 2).

As circuit II is a typical circuit for the ion current method, the rising time of the ion current signal obtained by such a circuit has been confirmed to correspond to the front edge of the luminous zone of the flamelet passing through the probe⁽⁷⁾. Therefore, from Fig.3 it is confirmed that, first, there exists a flame plasma^{*1} potential in the flamelet, which can be detected using circuit I and; second, the rising time of the plasma potential signal is nearly the same as that

Fig. 3 Flame potential signal (m_1) and ion current signal (m_2) from the same laminar flame

*1 In a plasma, the concentration of the positive ions is the same as that of the negative ones. When all the negative ions in the flamelet are supposed to be electrons and have the same kinetic energy as the positive ones, it is shown in Ref. (8) that a flamelet showing a positive electric potential signal by circuit I is not an exact plasma. Nevertheless, we regard the flamelet as a plasma for convenience.

of the ion current signal obtained by the ion current method. Therefore, a flamelet can be detected by its plasma potential signal using a probe without any externally-supplied electric potential; this is the so-called "flame potential method".

3.2 Discussion of the flame potential method

There are two basic requirements for an electrostatic probe used to detect flamelets from turbulent flames: a high spatial resolution and only a small influence on the flame. In order to improve the spatial resolution of the probe, it is necessary not only to reduce the size of the probe, but also to minimize the thickness of the ion sheath surrounding the probe, which results from the electric potential supplied to the probe.

In order to investigate the influence of the externally-supplied electric potential on the spatial resolution of the ion probe, different electric potentials were sequentially supplied to the same probe to detect the same laminar flame (by controlling the experimental conditions strictly, a laminar flame is easily reproducible). The obtained ion current signals (including the flame potential signal, which was obtained when $E=0$ V) are shown in Fig. 4. As shown by signals 1 to 3, the larger the electric potential which was negatively charged to the probe, the wider the ion current signal obtained. This result explains the fact that the thickness of the positive ion sheath increases with the negatively charged electric potential of the probe⁽⁴⁾. Although signals 3 to 5 show that a higher positive electric potential in the probe resulted in a narrower ion current signal, a positive electric potential supplied to the probe often resulted in a negative part in the ion current signal, as shown by signal 5, which is a possible factor affecting the next signal (spike)

Fig. 4 Influence of externally-supplied electric potential on ion current signal

from the next coming flamelet in the case of turbulent flames.

In addition, as far as the negatively charged electrostatic probe is concerned, it is known from Calcote's work⁽⁴⁾ that an ion sheath surrounding the probe exists. Such a sheath not only increases the width of the ion current signal, as shown in Fig. 4, resulting in a decrease in the spatial resolution of the probe, but also makes it difficult to compare experimental results with different electric potentials supplied to the probe. Moreover, when such a probe is used to investigate the structure of turbulent flames, the structure may have been affected by the electric field around the probe before it is detected since the flames have complicated electric properties.

For the above reasons, the flame potential method was applied to the investigation of turbulent flame structure in this work.

4. Investigation of the Turbulent Flame Structure

4.1 Typical flame potential signals and conceptual turbulent flame structure deduced from the signals

Knowledge of the premixed turbulent flame structure is of fundamental importance for the understanding and controlling of the combustion process in homogeneous-charge engines and in the formulation of combustion models. Therefore, increasingly more studies on the turbulent flame structure have been carried out recently. As far as theoretical studies are concerned, it is worth mentioning a model proposed by Tabaczynski et al.⁽⁹⁾ in 1980 for the turbulent flame structure. Based on Tennekes' turbulence structure model⁽¹⁰⁾, this model implies the existence of reactant islands behind the flame front.

On the other hand, owing to the development of techniques, remarkable progress has been made in the visualization of the flame structure in recent years. For example, the schlieren photographs of turbulent flames in a homogeneous-charge research engine have been obtained by Smith⁽¹¹⁾, showing the complicated schlieren fringes increasing rapidly with the engine speed; such schlieren photographs of premixed turbulent propagating flames in a constant-volume vessel have also been obtained by the authors⁽⁵⁾, which show the schlieren fringes increasing rapidly with the turbulence intensity. From the results of these experiments, it can be interpreted that, when the turbulence is intensified to some extent, some reactant islands are formed behind the flame front, whose individual schlieren images are superimposed on the overall image⁽⁵⁾. However, as a schlieren image integrates all the information along the light path, it cannot directly visualize the flame structure, and therefore its analy-

sis had to be based on some assumptions of the flame structure⁽⁵⁾.

This difficulty is expected to be overcome by laser-sheet tomography, which visualizes the flame structure directly. Two-dimensional images of turbulent flames have been obtained by Baritaud and Green⁽¹²⁾, showing some islandlike reactants existing behind the flame front (or the postflame region⁽¹²⁾). However, from another experiment⁽¹³⁾ also using laser-sheet tomography, it was reported that no reactant islands were found in the turbulent flames of an experimental engine.

In order to investigate the deep structure of turbulent flames behind the flame front, the flame potential method developed in this work was used. The size of the probe used was 0.2 mm in diameter and 0.6 mm in length, and the supporting tube of the probe was 0.8 mm in diameter. Some typical flame potential signals are shown in Fig. 5, which were detected from the premixed propagating turbulent flames of mixture 43-P 10-23 with a turbulence intensity (u') of 2.45 m/s, at 25 mm from the combustion chamber center.

In the case of laminar flames, only one spike exists in each flame potential signal, owing to the fact that there was only one flamelet passing through the probe. However, in the case of turbulent flames, often more than one spike exist in each flame potential signal, as shown in Fig. 5. As each spike can be identified with a flamelet passing through the probe, the result is explained as more than one flamelet existing in the flame. Indeed, the same result can also be explained as a single flamelet (the flame front) repeatedly passing through the probe, but this explanation seems unlikely because the flame propagation

Fig. 5 Typical flame potential signals and conceptual flame structure deduced from the signals

speeds (about 15 m/s) were much higher than the velocity fluctuations of the turbulence (about 2.5 m/s) in this experiment. Attributing each spike to a different flamelet in the flame zone, we deduced the flame structure, as illustrated in Fig. 5, conceptually, where the signals indicated by A, B, C etc., were respectively attributed to the locations of the flame specified by the corresponding letters. As many of the signals had as many as three to six spikes in each signal in this experiment, we conclude that the results of this experiment suggest that reactant islands are formed behind the flame front when the turbulence is intensified to some extent.

4.2 Methods of measuring the flame propagation speed and flame zone thickness

To begin with, it is necessary to provide a definition for the flame zone of a turbulent flame. Here, it is defined as the space within which flamelets exist. When measured by an electrostatic probe, the thickness of the flame zone was identified with the spatial length corresponding to the time interval from t_{st} to t_{end} , as shown in Fig. 6, where t_{st} and t_{end} correspond to the front edge and rear edge of the zone, respectively. In this work, t_{st} was called the front edge arrival time and t_{end} the rear edge arrival time.

With the definition for the flame zone, we can now discuss the flame propagation speed. So far, the propagation speed of a flame has been referred to as that of the front edge of the flame zone in most cases, especially in the case of laminar flames. However, in the case of turbulent flames, the propagation speed of the rear edge is not necessarily the same as that of the front edge, according to the measurements in this work; we measured both of them.

In order to obtain the propagation speed of the front edge, we first measured its arrival times at different locations at intervals of 5 mm along the radial direction of the combustion chamber. At each location, the same measurement was repeated at least 30 times to obtain the average arrival time. The average arrival times at different radial locations were then regressed on a single variable, r , the radial

distance from the combustion chamber center, using the least squares method. Thus, the time which the front edge takes to propagate to any radial distance r from the center can be estimated by the regression equation of t_{st} on r , in the form of a polynomial. Therefore, the propagation speed of the front edge, V_{st} , can be calculated by

$$V_{st} = dr(t_{st})/dt_{st} \quad (1)$$

Similarly, for the rear edge of the flame zone, we have

$$V_{end} = dr(t_{end})/dt_{end} \quad (2)$$

where V_{end} is the propagation speed of the rear edge.

On the other hand, the thickness of the flame zone was measured by three different methods as follows.

(a) Constant flame propagation speed method

In this method, the flame zone was considered to pass through the probe at a constant speed of V_{st} during the period of Δt . Thus, the flame zone thickness, d_r , can be calculated by

$$d_r(r) = \Delta t(r) \cdot V_{st}(r) \quad (3)$$

This method has been used because of its simplicity. However, as the measured Δt was rather large, during which the variation in V_{st} was not negligible, and as V_{end} appeared different from V_{st} , this method is not expected to provide accurate thicknesses.

(b) Double-probe method

This is a statistical method in which two probes were located at the same radial line, the separation distance between them being x , as shown in Fig. 7. The flame potential signals from probes a and b were divided into two groups according to the sequence of $t_{end,a}$ and $t_{st,b}$ being observed, where $t_{end,a}$ is the arrival time of the rear edge at probe a , and $t_{st,b}$ is that of the front edge at probe b (see Fig. 7).

For the first group, $t_{st,b}$ was observed earlier than $t_{end,a}$, that is, $t_{end,a} > t_{st,b}$. This relation means that the front edge had passed through probe b before the rear edge reached probe a . Therefore, it was reasoned that the thickness of the flame zone, d_r , must have been greater than the separation distance x . We then wrote $P(d_{ri} \leq x) = 0$, where $P(d_{ri} \leq x)$ is the probability that the thickness of the flame zone in the i -th experiment,

Fig. 6 Definition of flame zone

Fig. 7 Measurement of flame zone thickness (double-probe method)

d_{Ti} , not be greater than the separation distance x .

For the second group, $t_{end,a} \leq t_{st,b}$. This means $d_{Ti} \leq x$; thus, $P(d_{Ti} \leq x) = 1$.

For each separation distance of the two probes, more than forty samples of the flame zone were measured to yield the probability, $P(d_T \leq x)$. Varying the separation distance x , one can obtain the probabilities for different separation distances, $P(d_T \leq x_j)$, where x_j is the j -th separation distance. The measured values of $P(d_T \leq x_j)$ were then regressed on x using the least squares method, making it possible to calculate the value of $P(d_T \leq x)$ for any x . The value of x solved from $P(d_T \leq x) = 50\%$ was regarded as the mean thickness of the flame zone, d_{TM} . Moreover, the pdf of the flame zone thickness, $f(x)$, can be obtained as follows:

$$f(x) = \frac{d[P(d_T \leq x)]}{dx} \quad (4)$$

Since the thickness of the flame zone obtained by this method does not depend on the propagation speed of the zone, the influences such as those of the variation in flame propagation speed and the expansion effect of the burned gases within the flame zone can be removed. Another advantage of this method is that the pdf of the flame zone thickness can be obtained from the same data. However, large quantities of experiments are required.

(c) Graphic method

In this method, the regression equations for the arrival times, t_{st} and t_{end} , which have been obtained in the measurement of flame propagation speeds, were plotted as two curves, as illustrated in Fig. 8. From such a graph, one can find that the mean thickness of the flame zone, d_{TM} , is equal to the radial distance from the rear edge (specified by t_{end}) to the front edge (specified by t_{st}) at the same arrival time, t , as shown

Fig. 8 Measurement of flame zone thickness (graphic method)

by Δr in the figure. If $r_{min} < r < r_{max}$, then $d_{TM} = \Delta r$; if $r \leq r_{min}$, the entire space enveloped by the front edge was regarded as the flame zone, as was the space from the rear edge to the wall of the combustion chamber if $r \geq r_{max}$.

4.3 Measurement results and discussion

4.3.1 Flame propagation speed The propagation speeds of the front edge and rear edge of the flame zone for mixture 43-P10-23 at two turbulence intensities are shown in Fig. 9. The mean thickness of the flame zone, d_{TM} , obtained by the graphic method is also involved in the figure. As shown in Fig. 9, when the radius of the flame sphere was small, there were some flamelets left in the center, so that no rear edge was observed. The rear edge did not appear until the front edge propagated to about 23 mm away from the center in the case of $u' = 2.45$ m/s and about 27 mm in the case of $u' = 3.67$ m/s. With an increase in the radius of the flame sphere afterward, the rear edge of the flame zone began to appear, behind which a space containing only burned gases existed. Once the rear edge of the flame zone appeared, it propagated much faster than the front edge. As a result, the thickness of the flame zone decreased as the radius of the flame sphere increased.

(a) $u' = 2.45$ m/s

(b) $u' = 3.67$ m/s

Fig. 9 Flame propagation speed and flame zone thickness by the graphic method

4.3.2 Flame zone thickness Comparing Fig. 9(a) with Fig. 9(b), one can see that the mean thickness of the flame zone increases with the turbulence intensity. Detailed results obtained at a distance of 30 mm away from the combustion chamber center by the graphic method show that the mean thickness of the flame zone of mixture 43-P10-23 is 7.4 mm when $u' = 1.47$ m/s, 17 mm when $u' = 2.45$ m/s, and 21.2 mm when $u' = 3.67$ m/s. Measured by the double-probe method at the same location, the pdfs of the flame zone thickness are given in Fig. 10, showing that the flame zone thickness increases with an increase in the turbulence intensity u' for the same mixture and/or a decrease in the Damköhler number Da for mixtures with the same turbulence intensity. Here, the Damköhler number Da has been defined⁽⁵⁾ as $Da = S_L L_f / (4u' \delta_L)$, where L_f is the longitudinal integral scale of the turbulence.

4.3.3 Separation distance between adjacent flamelets in the flame zone The average separation distance between adjacent flamelets in the flame zone, as well as the mean thickness of the zone, is an important parameter for the turbulent flame struc-

ture. It was identified by the spatial distance corresponding to the average time interval between successive spikes in the flame potential signal. The average separation distance obtained appears to be somewhat smaller in cases where the turbulence intensities are low and/or the laminar burning velocities of mixtures are high in comparison with other cases. For flames with moderate turbulence intensities, its values were about two times the longitudinal integral scale of the turbulence, L_f . For example, for mixture 43-P10-23 at turbulence intensities of 2.45 and 3.67 m/s, its values were about 6.9 and 7.9 mm, respectively, while the values of L_f were about 3.5 mm. The average separation distance between adjacent flamelets is considered to be a parameter related to the mean size (diameter, represented by X_c) of the initially convoluted reactant islands. In a previous study⁽⁵⁾, X_c was assumed to be on the order of L_f . If this assumption is true, the measured separation distance between adjacent flamelets is larger than the size of reactant islands. This result is attributed to the expansion effect of the burned gases in the flame zone, which increases the distance between adjacent reactant islands (and thus the adjacent flamelets).

4.3.4 Influences of the Damköhler number and the Reynolds number on the turbulent flame structure The Damköhler number and the Reynolds number are regarded as the two principal parameters governing the turbulent flame structure. In this work, the Reynolds number was mainly controlled by the turbulence intensity and the Damköhler number by the properties of the mixture. On the other hand, the flame structure was quantitatively represented by the number of flamelets in the flame zone. The distributions (shown as pdfs) of the flamelet number in the flame zone are shown in Fig. 11(a) for the same mixture at different turbulence intensities and in Fig. 11(b) for different mixtures at the same turbulence intensity. From Fig. 11, one can see that the flamelet number in the flame zone increases with an increase in the turbulence intensity for the same mixture and/or a decrease in the Damköhler number for mixtures with the same turbulence intensity.

5. Comparison of the Measurements and Model Predictions of the Flame Zone Thickness

On the basis of the schlieren photographs of premixed turbulent propagating flames, the authors proposed a model⁽⁵⁾ for the fine structure of the flames. In the model, the flamelets in the flame zone consisted of two parts: a continuous, wrinkled flame front and some reactant-island flamelets behind the flame front. The fractions of these two parts were supposed to vary continuously with the Reynolds number and the

Fig. 10 Influences of turbulence intensity and Damköhler number on distribution of flame zone thickness

Fig. 11 Influences of turbulence intensity and Damkohler number on number of flamelets in flame zone

Damköhler number. According to the model, the mean thickness of the flame zone, d_{TM} , can be estimated by

$$d_{TM} = \tau_M \cdot V_M, \quad (5)$$

where τ_M is the characteristic burn-up time of the turbulent flame zone⁽⁵⁾, and V_M is the reactant-island average speed relative to the flame front. In the case when the pressure rise caused by combustion is negligible and the flame propagation is one-dimensional, the relative speed V_M can be approximated by the following equation :

$$V_M \approx S_T(1 + T_b/T_u)/2, \quad (6)$$

where S_T is the turbulent burning velocity⁽⁶⁾, T_b and T_u are the temperatures of the burned and unburned gases, respectively, with T_b being given the constant-pressure adiabatic flame temperature shown in Table 1.

To calculate τ_M with the model⁽⁵⁾, the mean size of the reactant islands was assumed to be the longitudinal integral scale of the turbulence. In Fig. 12, the model-predicted flame zone thicknesses are compared with the measured ones which were obtained at 30 mm from the center of the combustion chamber (when the radius of the flame sphere was about 30 mm, the pressure rise caused by combustion was very small in this experiment). In the figure, "Method a", "Method b" and "Method c" represent the "constant flame

Fig. 12 Comparisons of measurements and predictions of flame zone thickness

propagation speed method", the "double-probe method", and the "graphic method", respectively. It is shown in Fig.12 that the model-predicted flame zone thicknesses are somewhat larger than the measured ones, especially in the case of large Damköhler numbers. Nevertheless, considering the uncertainties associated with both the data and the predictions, the agreement between them is quite good. Therefore, the measurements are considered to support the model.

6. Conclusions

(1) A flame plasma potential exists in the flamelet of premixed propagating flames, which can be used to detect the flamelet. An electrostatic probe working on the flame potential method not only has a higher spatial resolution than one working on the ion current method, but also minimizes the electric influence of the probe on the flame structure.

(2) Many of the flame plasma potential signals obtained from premixed turbulent propagating flames show more than one spike in each signal ; this phenomenon can be attributed to more than one flamelet existing in the flame zone. Moreover, the number of flamelets in the flame zone increases with an increase in the turbulence intensity for the same mixture and/or a decrease in the Damköhler number for mixtures at the same turbulence intensity.

(3) For a spherical propagating flame of the premixed turbulent mixture, the flame zone thickness increases as the turbulence is intensified. The rear edge of the flame zone propagates faster than the front edge. As a result, the flame zone thickness decreases as the diameter of the flame sphere increases.

(4) The average separation distance between

adjacent flamelets in the flame zone is about two times the longitudinal integral scale of the turbulence when the turbulence is intensified to some extent ($u' = 2 \sim 4$ m/s in the experiment).

(5) The flame zone thicknesses predicted by the model proposed by the authors⁽⁵⁾ are in good agreement with those measured, despite the fact that the former are somewhat larger than the latter; this result supports the model.

Acknowledgments

This work was partially supported by Grant-in-Aid for Scientific Research No.63550166 from the Ministry of Education, Science and Culture of Japan, and also by Grant-in-Aid for General Research of Science and Technology from the Yazaki Foundation.

References

- (1) Suzuki, T., Kudo, N., Kawamata, M. and Hirano, T., Simultaneous Measurements of Gas Flow and Flame Front Movement in a Turbulent Premixed Flame Zone, Proc. 21 st (Int.) Symp. Combust., (1986), p.1385.
- (2) Calcote, H. F. and King, I. R., Studies of Ionization in Flames by Means of Langmuir Probes, 5 th (Int.) Symp. Combust., (1955), p.423.
- (3) Hirano, T., Ion-Current Fluctuation Recorded with a Cylindrical Electrostatic Probe Passing Premixed Flames, Combust. Flames, Vol.36, (1979), p. 179.
- (4) Calcote, H. F., Ion and Electron Profiles in Flames, Proc. 9 th (Int.) Symp. Combust., (1963), p.622.
- (5) Kido, H., Nakashima, K., Huang, S. and Kitano, K., A Study on the Fine Structure of Propagating Turbulent Flames in Premixed Mixtures (An Analysis of the Schlieren Images Based on a Flame Structure Model), JSME Int. J., Series II, Vol.33, No.2, (1990), p.362.
- (6) Kido, H., Wakuri, Y. and Nakashima, K., Experiments and a Correlation of Turbulent Burning Velocities, Proc. 1983 ASME-JSME Thermal Eng. Joint Conf., Vol.4 (1983), p.183.
- (7) Calcote, H. F., Ion Production and Recombination in Flames, Proc. 8 th (Int.) Symp. Combust., (1962), p.184.
- (8) Kido, H., Huang, S. and Nakashima, K., Measurement of the Premixed Turbulent Propagating Flames Using an Electrostatic Probe, (1 st Report, Laminar Flames), Proc. 26 th (Japanese) Symp. on Combust., (in Japanese), (1988), p.7.
- (9) Tabaczynski, R. J., Trinker, F. H. and Shannon, B. A. S., Further Refinement and Validation of a Turbulent Flame Propagation Model for Spark-Ignition Engines, Combust. Flame, Vol.39, (1980), p.111.
- (10) Tennekes, H., Simple Model for the Small-Scale Structure of Turbulence, Phys. Fluids, Vol.11, No. 3 (1968), p.669.
- (11) Smith, J. R., Turbulent Flame Structure in a Homogeneous-Charge Engine, SAE Trans., 91, Sec.1 (1982), p.150.
- (12) Baritaud, T. A. and Green, R. M., A 2-D Flame Visualization Technique Applied to the I.C. Engine, SAE Trans. Vol.95, Sec.1 (1986), p.1.197.
- (13) Mantzaras, J., Felton, P. G. and Bracco, F. V., Three-Dimensional Visualization of Premixed-Charge Engine Flames: Islands of Reactants and Products; Fractals Dimensions; and Homogeneity, SAE Paper, No.881635, (1988).