Turbulent Premixed Flames in a Closed Vessel Studied Through Analysis of Flame Photographs*

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The characteristics of roughness of a turbulent flame front in a disc-type combustion chamber were determined through high-speed schlieren photography and image analysis. The correlations between the characteristics of flame-front roughness and the turbulence characteristics or the turbulent burning velocity were discussed. The main results were as follows: (1) The RMS value " $\bar{\alpha}$ " and the integral scale " $\bar{L}_f$ " of the flame-front roughness are strongly influenced by the intensity and the integral spatial scale of turbulence. (2) The shape of the power spectrum of flame-front roughness is similar to that of the power spectrum of turbulent flow, and the microscale of the flame-front roughness is nearly equal to the Taylor microscale of turbulence. (3) The ratio of turbulent burning velocity to laminar burning velocity, S_T/S_L , is proportional to the value of $\sqrt{1+(2\bar{\alpha}/\bar{L}_f)^2}$.

Key Words: Combustion, Turbulent Flame, Roughness of Flame Front, Image Analyzing, Turbulent Burning Velocity

1. Introduction

The flame-front roughness of a turbulent premixed flame propagated in a closed combustion chamber, such as a spark-ignition engine, appears to be influenced by the turbulence characteristics of flow. Smith⁽¹⁾ observed the flames in an engine cylinder using a pulsed microschlieren technique and showed that the scale of the flame structure decreased with an increase in the turbulence Reynolds number. Saitoh and Kawamura⁽²⁾ analyzed the flames in an engine with a high-speed-shutter TV camera and an image-analyzing system, and reported that the short wavelength components of flame-front roughness increased with either the lapse of time from ignition or the engine speed. Cross sections of the flame front were examined, using a two-dimensional visualization technique employing a pulsed laser sheet and a diode array, by Loye, Bracco and Santavicca⁽³⁾ and Loye and Bracco⁽⁴⁾. However, the correlations between the

turbulent flame-front roughness and the turbulence characteristics have not yet been made clear.

In this study, a swirling flow of a propane-air homogeneous mixture was produced in a disc-type combustion chamber by charging the mixture tangentially. At the center of the combustion chamber, the mixture was ignited by an electric spark, and a turbulent flame which propagated nearly axisymmetrically was thereby produced. Through analysis of high-speed schlieren photographs of flames, the characteristics of flame-front roughness were determined, and the correlations between them and the turbulence characteristics were investigated. Moreover, the turbulent burning velocity was expressed successfully in terms of the characteristics of flame-front roughness.

2. Experimental Conditions

In this paper, only a brief outline of the experimental apparatus will be given. The details were presented in the previous paper⁽⁵⁾. The combustion chamber was a cylindrical vessel 125 mm in diameter and 35 mm wide. Before the valve was opened, the pressure of the mixture in the combustion chamber was set at 50 kPa, and that in the mixture tank was

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set at 300 kPa or 400 kPa (denoted as 50~300 kPa or 50~400 kPa, respectively). A homogeneous mixture propane and air (equivalence ratios: $\phi=0.8, 1.0, 1.2$ and 1.4) stored in the mixture tank flowed into the combustion chamber through the charging valve, which was forced open for 200 ms, and a swirl flow was produced. The swirl flow decayed with the lapse of time. Table 1 shows the experimental conditions. The value of $(TI)_v$ denotes the spatial mean value of the turbulence intensity at the time of ignition, t_{ig} , which is the elapsed time after valve closure. By calculating the angular momentum of swirl from the tangential mean velocity, we determined the angular velocity of solid body rotation, Ω , as the representative velocity of swirl. The pressure, p_i , and the temperature, T_i , at the time of ignition are shown in Table 1, where T_i was determined as $T_i = p_i V / (MR)(V$ denotes the volume of the chamber, M the mass of mixture and R the gas constant). Under these five conditions, the mixture was ignited by an electric spark at the center of the vessel, and the flames propagated in the swirl flow were observed by high-speed schlieren photography (light source: 50 mW He-Ne laser, film speed: 4 000 frames/s).

3. Image Analysis of Flame Photographs

The flame photographs obtained by high-speed schlieren photography were digitized using a TV-camera input system (512×512 pixel resolution, 256 brightness level). The image data of the flames were processed to a binary expression at a suitable threshold level of brightness to emphasize the flame front, and thus the values of the coordinates of the flame front were obtained. Figure 1(a) shows typical schlieren photographs of flames under the conditions of differing turbulence intensities, and the contours of flames obtained by processing these images are shown in Fig. 1(b). When the swirl velocity, Ω , is increased, the turbulence intensity increases, and the flame front is more disturbed.

As shown in Fig. 2, the mean flame front is defined as the arc with the radius corresponding to the average value ($=r_{fi}$) of the distance ($=r_i(l)$) from the

spark point to the flame front. The fluctuating component ($=r'_i(l)$) of the flame front from the arc is expressed as follows:

$$r'_i(l) = r_i(l) - r_{fi} \quad (1)$$

where l denotes a length on the arc of the mean flame front. Since the value of $r_i(l)$ is determined at every 0.1 mm, the number of the measuring point is 200 in the case of an arc length, Δl , of 20 mm. The use of Δl of 20 mm is equivalent to the use of a high-pass filter having a cutoff wave number of about 25 m^{-1} . The contour of the flame front is divided into N pieces ($=4\sim8$) of measuring segments. The roughness characteristics of the turbulent flame front are defined by the following equations.

Mean radius of flame :

$$r_f = \frac{1}{N} \sum_{i=1}^N r_{fi} \quad (2)$$

RMS value of fluctuating components :

$$\alpha = \sqrt{\frac{1}{N} \sum_{i=1}^N r'_i(l)^2} \quad (3)$$

Auto-correlation coefficient :

$$R_f(x) = \frac{1}{\alpha^2} \frac{1}{N} \sum_{i=1}^N \left[\frac{1}{\Delta l - x} \int_0^{\Delta l - x} r'_i(l) r'_i(l+x) dl \right] \quad (4)$$

$$[x = \text{length}, 0 \leq x \leq x_{\max}, x_{\max} = \Delta l/2, \Delta l = 20 \text{ mm}]$$

Power spectrum :

$$E_f(k) = 4\alpha^2 \int_0^{x_{\max}} R_f(x) w(x) \cos(2\pi kx) dx \quad (5)$$

where k is the wave number, and $w(x)$ is the window function:

$$w(x) = (1 + \cos(\pi x/x_{\max}))/2.$$

Normalized power spectral density :

$$F_f(k) = E_f(k)/\alpha^2 \quad (6)$$

Integral scale : $L_f = x_L$,

$$[R_f(x_L) = 1/e, e = 2.71828] \quad (7)$$

Microscale :

$$\lambda_f = 1 / \sqrt{2\pi^2 \int_0^{k_{\max}} k^2 F_f(k) dk} \quad (8)$$

$$[k_{\max} = 10\,000 \text{ m}^{-1}]$$

From gas velocities measured with LDA, the turbulence characteristics⁽⁵⁾ were determined by the stationary time-average method⁽⁶⁾. The integral spatial scale, L_v , was determined by spatially averaging the values of L , which were determined by multiplying the integral time scale by the mean swirl velocity. The power spectrum, $E(k)$, was determined by averaging in the three mutually orthogonal directions. In addition, the micro spatial scale, λ_v , was determined as follows⁽⁷⁾:

$$\lambda_v = L_v \sqrt{15} \{ (TI)_v L_v / \nu \}^{-0.5}, \quad (9)$$

where ν denotes the kinematic viscosity. As these values were determined using the averaging time interval of 5 ms, the fluctuating components of the velocity with frequencies lower than about 100 Hz

Table 1 Experimental conditions

No.	t_{ig}, ms	$\Omega, \text{rad/s}$	$(TI)_v, \text{m/s}$	kPa	p_i, kPa	T_i, K
1	10	139.1	0.33	50-300	243	325
2	100	108.2	0.21		238	318
3	300	65.6	0.14		221	298
4	10	178.2	0.38	50-400	326	331
5	100	129.7	0.25		322	326

Fig. 1 Schlieren photographs of flames (a) and contours of flames after image processing (b) (50~300 kPa, $\phi=1.0$)

were cut off⁽⁸⁾.

4. Experimental Results

Figure 3 shows the effect of the turbulence intensity, $(TI)_v$, on the RMS value of fluctuating components, $\bar{a}$, and the integral scale, $\bar{L}_f$, of the turbulent flame-front roughness. The symbol “—” refers to the time-averaged value. The mean radii of flames analyzed were from 29 mm to 59 mm, and ten photographs were used. The values of $\bar{a}$ and $\bar{L}_f$ increase with an increase in the turbulence intensity, $445(TI)_v$. As shown in Fig. 4, there is also a strong correlation between the value of $\bar{L}_f$ and the integral spatial scale of flow, L_v . Furthermore, as shown in Table 2, the microscale of turbulent flame-front roughness, $\bar{\lambda}_f$, is nearly equal to the micro spatial scale of turbulence, λ_v .

The turbulence characteristics were determined

Fig. 2 Definition of flame-front roughness

Table 2 Microscale (50~300 kPa, $\phi=1.0$)

No.	Ω , rad/s	$\bar{\lambda}_f$, mm	λ_v , mm
1	139.1	1.1	1.0
2	108.2	1.0	1.0
3	65.6	0.9	1.1

Fig. 3 Effect of $(TI)_v$ on $\bar{\alpha}$ and $\bar{L}_f$ Fig. 4 Correlation between $\bar{L}_f$ and L_v

under the condition of an absence of combustion because the integral spatial scale, $L(\text{burn})$, of the unburned gas during the flame propagation was almost equal to L_v under the condition of an absence of combustion, as shown in Fig. 5.

Figure 6 shows the power spectrum of turbulent flow, $E(k)$, and that of turbulent flame-front roughness, $E_f(k)$, in almost the same wave number region. $E(k)$ is the spatial averaged value of the spectra determined at the positions of $X=30, 40$ and 50 mm. $E_f(k)$ is the spectrum of the flame whose mean radius, r_f , was about 50 mm. As shown in Fig. 6, the shape of the power spectrum of turbulent flame-front roughness, $E_f(k)$, was similar to that of the power spectrum of turbulent flow, $E(k)$. The flame-front roughness appears to be affected by the structure of turbulence. When the swirl velocity, Ω , increases, the power

Fig. 5 Correlation between $L(\text{burn})$ and L_v Fig. 6 Power spectra of turbulence (a) and of turbulent flame-front roughness (b) (50~300 kPa, $\phi=1.0$)

Fig. 7 Normalized power spectral density (50~300 kPa, $\phi=1.0$)

spectrum of the flame-front roughness has a large value all over the wave number. As shown in Fig. 7, the shapes of the power spectral density, $F_r(k)$, normalized by the value of α^2 were almost the same, even when Ω changed.

Schelkin⁽⁹⁾ assumes, under the condition of weak turbulence, that the configuration of turbulent flame-front roughness is conic, and that the ratio of turbulent burning velocity to laminar burning velocity, S_T/S_L , is proportional to the ratio of the conical surface area to the bottom area of the cone. The characteristic values of flame-front roughness, $\bar{\alpha}$ and $\bar{L}_f$, obtained by the image analysis correspond to the height and the diameter of the bottom of the cone, respectively. By applying Schelkin's model, we can express S_T/S_L as follows:

$$S_T/S_L = b\sqrt{1 + (2\bar{\alpha}/\bar{L}_f)^2}, \quad (10)$$

where b is an empirical constant. This correlation was examined using the measured values of $\bar{\alpha}$, $\bar{L}_f$ and S_T/S_L , and its result was shown in Fig. 8. The values of S_T/S_L in this figure are the averages of the values determined at the flame radii of 30, 40 and 50 mm. It is recognized that the value of S_T/S_L proportionally increases with the value of $\sqrt{1 + (2\bar{\alpha}/\bar{L}_f)^2}$, and Schelkin's conical model can be applied under the condition of weak turbulence.

5. Conclusions

High-speed schlieren photographs of a premixed

Fig. 8 Correlation between S_T/S_L and $\sqrt{1 + (2\bar{\alpha}/\bar{L}_f)^2}$

turbulent flame propagated in a closed vessel were analyzed. The correlations between the characteristics of roughness of the flame front and the turbulence characteristics or the turbulent burning velocity were discussed. The following results were obtained:

- (1) The characteristic values of flame-front roughness, $\bar{\alpha}$ and $\bar{L}_f$, are strongly influenced by the intensity and the integral spatial scale of turbulence.
- (2) The shape of the power spectrum of turbulent flame-front roughness is similar to that of the power spectrum of turbulence.
- (3) The microscale of turbulent flame-front roughness is almost equal to the micro spatial scale of turbulence.
- (4) The ratio of turbulent burning velocity to laminar burning velocity, S_T/S_L , is proportional to $\sqrt{1 + (2\bar{\alpha}/\bar{L}_f)^2}$. It is recognized that Schelkin's model is useful for flames in weak turbulence.

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