Propagation Properties of Turbulent Premixed Flames
Neutral for Thermo-Diffusive Effects

Toshiaki Kitagawa 1) Hiroaki Watanabe 1) Ryou Nishiyama 1) Riou Sonokawa 1) Kenichi Shinoda 1)
1) Kyushu University, Faculty of Engineering
744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan (E-mail: toshi@mech.kyushu-u.ac.jp)

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ABSTRACT: Burning velocity is one of the important properties of premixed turbulent flames. Premixed turbulent flames are, in general, subjected to the thermo-diffusive effects in addition to the increase in the flame front area due to the influence of turbulence. In order to independently evaluate these two effects on turbulent flames and their burning velocity, ethane flames, which have a Lewis number around unity and can therefore be considered insensitive to the thermo-diffusive effects, were examined. Flame front morphologic properties such as a Fractal dimension were obtained by Fractal analysis of flame front tomography, and burning velocity was obtained by Schlieren technique. A novel correlation of turbulent burning velocity with Fractal properties of flame front was proposed.

KEY WORDS: Heat engine, Spark ignition engine, Combustion analysis / Turbulent burning velocity, Thermo-diffusive effects, Fractal analysis, Correlation of burning velocity [A1]

1. Introduction

In spark ignition engines, premixed flame propagates in turbulent flow field. Its burning velocity is one of the important factors for the performance of the engines. In general, burning velocity of premixed flame increases with turbulence intensity of the unburned mixture flow within weak to moderate turbulence intensity ranges. Wrinkling of the flame front caused by turbulent eddies increases the flame front area(1),(3). And it consequently increases the consumption rate of the unburned mixture.

The enhancement of turbulent combustion is considered effective to improve the thermal efficiency of the engines because the diminish of the combustion duration leads to the increase in the constant volume degree of the thermodynamic cycle. Thus, the intensification of in-cylinder turbulent motion has been examined to increase the turbulent burning velocity of the flame(6).

On the other hand, turbulent flame is subjected by the thermo-diffusive effects due to the flame stretch which is caused by the turbulent eddies(1),(3). Local burning velocity of the flamelet is considered to vary from the unstretched laminar burning velocity. Turbulent burning velocity depends both on the increase in the flame front area and on the variation of local burning velocity of flamelet due to the thermo-diffusive effects.

The thermo-diffusive effects depend on the mixture properties such as fuel, its concentration and pressure. Kitagawa showed the ratio of the turbulent burning velocity to the unstretched laminar burning velocity varied with the fuel concentration even at a fixed intensity and length scale of turbulence. Furthermore, this tendency depends on the type of fuel(3),(7),(10). In addition to them, Kitagawa showed that quenching of flame kernel occurred for the rich methane-air flame whereas the lean flame propagated very fast although these rich and lean laminar flames have the same unstretched laminar burning velocity(6).

Considering these knowledge, it is important to clarify respective quantitative contribution of the increase in the flame front area and the variation of local burning velocity due to the thermo-diffusive effects on the turbulent burning velocity. It is useful for the understanding of the turbulent flame propagation mechanism and the modeling of the turbulent burning velocity.

For laminar premixed flames, the variation of the burning velocity due to the thermo-diffusive effects is evaluated by the Lewis number and the Markstein number(3),(9),(11). For turbulent flames, however, the increase in the flame front area and the variation of the local burning velocity of flamelet occur simultaneously. In general, it is difficult to evaluate each effect independently.

In this study, in order to independently evaluate these two effects on turbulent flames and their burning velocity, ethane flames, which have a Lewis number around unity and can therefore be considered insensitive to the thermo-diffusive effects, were examined. Ethane turbulent flames might be affected only by the increase in the flame front area.

Spherically propagating ethane-air laminar and turbulent flames in a fan-stirred constant volume bomb were examined. For laminar flames, their properties such as the laminar burning velocity and the Markstein number were obtained. For turbulent flames, flame front area is related to the flame front morphology. Flame front morphologic properties such as a Fractal dimension were obtained by Fractal analysis of flame front tomography, and burning velocity was obtained by Schlieren technique. A novel correlation of turbulent burning velocity with Fractal properties of flame front was proposed.
2. Methodology

2.1. Experimental apparatus

Experiments of laminar and turbulent explosions were carried out using the constant volume combustion vessel outlined schematically in Fig. 1 (3). The combustion chamber was comprised of three 265 mm diameter cylinders which intersected orthogonally. The total volume of the chamber was approximately 35 liters or equivalent to that of a sphere with a diameter of 406 mm. The vessel was designed to withstand the combustion pressure of up to 10 MPa. Ethane-air mixture was prepared in the chamber according to the required partial pressure of each component. Two fans were mounted at the top and bottom of the chamber and driven by electric motors in order to ensure mixing of mixture components and to generate homogeneous and isotropic turbulent flow motion.

Mixture was ignited by electric spark at the center of the chamber. Two spark electrodes of 1.6 mm in diameter were inserted diagonally in the chamber oppositely. Spark gap was set to 3 mm and the spark energy was 1.4 J. Equivalence ratio, $\phi$ of the mixture was set to 0.8, 1.0 and 1.4. Initial mixture pressure, $P_i$ was 0.50 MPa. Initial temperature of the mixture, $T_i$ was set to 340 K.

Spherically propagating laminar and turbulent flames in the chamber were examined. Pressure history during the explosion was recorded. At least five experiments were carried out at each condition.

In the turbulent explosions, turbulence intensity, $u'$ was set to 1.23 and 2.46 m/s. The characteristics of turbulence in the chamber were evaluated by particle image velocimetry (PIV) by the same manner done by Hayakawa and Kitagawa et al. (3). Longitudinal integral length scales of turbulence, $L_f$ was 27.96 mm irrespective of the turbulence intensity.

Flame propagation was observed via three 160 mm diameter optical windows mounted at the sides of the chamber. Optical system is shown in Fig. 2. The spatial distributions of burned gas and unburned mixture during the propagation were analyzed from the Mie scattering of TiO$_2$ particles in a thin planar laser light sheet. The cw-Nd:YAG laser light sheet was introduced in to the chamber from the window so that it passed the spark gap located at the center of the chamber. Tomograph images were recorded through the second optical window from the orthogonal direction to the laser sheet with a high speed camera. Schlieren images were also recorded simultaneously with another high speed camera using a xenon lamp as a light source through the third window arranged at the opposite side of the second one.

3. Results and discussion

3.1. Laminar burning velocity and Markstein number

Schlieren image of the laminar flame at the instant of the flame radius, $r_{sch} = 45$ mm is shown in Fig. 3(a). Because...
turbulent flame may consist of laminar flamelets when turbulence intensity is weak or moderate as examined in this study, laminar flame properties are important as the basis of the analysis of turbulent flames. Wrinkles due to the flame instability\(^{1(10)}\) on the smooth flame front are observed at this flame radius at all the equivalence ratios, \(\phi = 0.8, 1.0 \text{ and } 1.4\).

Propagating flame speed was obtained by time differentiation of flame radius, \(r_{\text{ach}}\) of the Schlieren images. Laminar burning velocity during the flame propagation, \(u_0\) was determined from the flame speed and the densities of unburned mixture and burned gas based on the conservation equation of mass. The laminar burning velocity \(u_0\) is generally varied from the unstretched laminar burning velocity \(u_t\) due to the flame stretch. For spherically propagating flames, the flame stretch rate, \(\alpha\) can be calculated by flame radius, \(r_{\text{ach}}\)\(^{(1)}\).

The difference between the stretched laminar burning velocity, i.e. laminar burning velocity during flame propagation \(u_0\) and the unstretched laminar burning velocity \(u_t\) is considered to be proportional to the flame stretch rate \(\alpha\). Markstein length, \(L\) was obtained as a slope of the linear relationship of \(u_0\) with \(\alpha\). The unstretched laminar burning velocity \(u_t\) was derived as the intercept value of \(u_0\) at \(\alpha = 0\) by the extrapolation of the stretched laminar burning velocity to the infinite flame radius or the stretch rate of zero\(^{(1)}\).\(^{(1)}\)\(^{(3)}\). Because the flame stretch rate is unknown due to the cellular flame front after the onset of flame instability, the above procedure was applied only in the range of stretch rates or flame radii where the flame was stable\(^{(1)}\)\(^{(3)}\).

The Markstein length, \(L\) was non-dimensionalized to Markstein number, \(Ma\) with the preheat zone thickness, \(\delta^0\). The preheat zone thickness of laminar flame was determined by \(\delta^0 = \delta (\rho_c C_p u_s)\), where \(\lambda\) and \(C_p\) are thermal conductivity and specific heat at constant pressure of the mixture, respectively. Flame thickness, \(\delta\) here follows the definition by Peters\(^{(10)}\).

The unstretched burning velocity, \(u_t\) and the Markstein number, \(Ma\) are shown in Figs. 4 and 5 respectively. The unstretched burning velocity, \(u_t\) was maximum at \(\phi = 1.0\) and small at \(\phi = 0.8\) and 1.4 as well as other hydrocarbons\(^{(3)}\)\(^{(1)}\).\(^{(1)}\). The Markstein number, \(Ma\) varied with the equivalence ratio, \(\phi\) but its value was around zero different from other fuels. For iso-octane flames\(^{(3)}\), \(Ma\) varies from about 3 at \(\phi = 0.8\) to -5 at \(\phi = 1.4\) at the same mixture temperature and pressure of 340 K and 0.50 MPa. It was confirmed that laminar burning velocity of ethane-air flames is not significantly affected by the flame stretch. This tendency does not depend on the equivalence ratio, \(\phi\). Note that the Lewis number calculated from the mixture properties is slightly larger at \(\phi = 1.4\) than that at \(\phi = 0.8\), and is around unity irrespective of \(\phi\).

3.2. Turbulent burning velocity

Table 1 shows the properties of turbulence in the examined conditions. Here, \(L_f\) is the longitudinal integral length scale of turbulence, \(\lambda_f\) is the longitudinal Taylor micro scale and \(\nu_f\) is the Kolmogorov length scale. \(Re_{\text{uf}}\) is the turbulence Reynolds number based on \(\lambda_f\). Turbulence Karlovitz number\(^{(15)}\) was also obtained for each turbulence intensity and the equivalence ratio although it is not shown in the table.

As shown in Fig. 6, the examined conditions were in the corrugated flamelets zone and the vicinity of the Klimov-Williams criterion on Peters combustion diagram\(^{(14)}\).

Figures 3(b) and (c) show Schlieren and tomograph images of turbulent flames at the flame radius, \(r_{\text{ach}} = 45\) mm. Wrinkles were

![Table 1 Properties of turbulence](image)

| \(u'\) m/s | \(L_f\) mm | \(\lambda_f\) mm | \(\nu_f\) mm | \(Re_{\text{uf}}\) |
|---|---|---|---|---|
| 1.23 | 27.96 | 1.36 | 0.033 | 443 |
| 2.46 | 27.96 | 0.96 | 0.020 | 626 |

![Fig. 6 Examined conditions on Peters diagram](image)
formed on the flame front by the interactions between turbulent eddies and flame front. More wrinkles seemed to be convoluted on the flame front in the case turbulence intensity, \( u' = 2.46 \text{ m/s} \) compared with the case, \( u' = 1.23 \text{ m/s} \). The flame front area might be increased by these wrinkling.

The turbulent burning velocity during the flame propagation, \( u_{bn} \) was calculated from the flame radius of Schlieren image as well as the laminar burning velocity. For turbulent flames, the Schlieren flame image has a wrinkled circumference. The radius of a circle which has an equivalent area to the Schlieren flame image was adopted as the flame radius, \( rsch \). The Schlieren image is the integrated one along the light path. Therefore, it is impossible to recognize three-dimensionally wrinkled flame front as what it is. However, Bradley et al. and Kitagawa (2) showed that this burning velocity correlated with the turbulent burning velocity obtained from the planer Mie-scattered image, and they also showed that this turbulent burning velocity was associated with the entrainment and mass consumption rate of unburned mixture.

Variations of the turbulent burning velocity, \( u_{bn} \) with flame radius, \( rsch \) are shown in Fig. 7. Average one among the explosions is shown in the figure at each condition. The turbulent burning velocity kept increasing during the flame propagation. It did not attain its maximum within the observation range in any case in this study.

In the case turbulence intensity, \( u' = 1.23 \text{ m/s} \), the turbulent burning velocity, \( u_{bn} \) was almost same throughout the observation range at all the three equivalence ratios, \( \phi = 0.8, 1.0 \) and 1.4. In the case turbulence intensity, \( u' = 2.46 \text{ m/s} \), the turbulent burning velocity, \( u_{bn} \) was larger at the equivalence ratios, \( \phi = 1.0 \) and 1.4 than that at \( \phi = 0.8 \).

The unstretched laminar burning velocity, \( u \) was different each other at the three equivalence ratios. In order to evaluate these variations of the turbulent burning velocity, \( u_{bn} \) taking the difference of \( u \) into consideration, ratio \( u_{bn} / u \) was examined as shown in Fig. 8. Value of the ratio of the turbulence intensity to the unstretched laminar burning velocity, \( u' / u \) is also shown for each condition in the figure.

In the case turbulence intensity, \( u' = 1.23 \text{ m/s} \), the ratio \( u_{bn} / u \) was almost same at the equivalence ratios, \( \phi = 0.8 \) and 1.4 where the unstretched laminar burning velocity, \( u \) was almost same. At \( \phi = 1.0 \), \( u_{bn} / u \) was smaller than those at \( \phi = 0.8 \) and 1.4. Same tendency of \( u_{bn} / u \) was observed in the case turbulence intensity, \( u' = 2.46 \text{ m/s} \), although \( u_{bn} / u \) at \( \phi = 0.8 \) was slightly smaller than that at \( \phi = 1.4 \). Further investigation is required on this relationship of \( u_{bn} / u \) between \( \phi = 0.8 \) and 1.4.

Larger \( u_{bn} / u \) at \( \phi = 0.8 \) and 1.4 and smaller one at \( \phi = 1.0 \) might be related mainly to the magnitude of \( u' / u \). Increase in \( u' \)
Kitagawa et al. investigated the dependence of the turbulent burning velocity on the equivalence ratio from the viewpoint of the variation of the Markstein number with the equivalence ratio. They showed that the ratio $u_b / u_l$ was larger for the flames whose Markstein number was smaller(3)-(7)-(10).

Turbulent flame is considered to consist of the flamelets which retain the nature of laminar flame within weak to moderate turbulence intensity ranges as examined in this study. Turbulent flame is stretched locally by turbulent eddies via aerodynamic strain and/or the flame curvature. Local burning velocity of flamelet might be varied from the unstretched laminar burning velocity due to the flame stretch. The thermo-diffusive effects play an important role for turbulent flames. As for the curvature, turbulent flames are stretched generally in a positive manner(16). Therefore, the property of the burning velocity variation by the positive flame stretch may reflect the turbulent burning velocity. Thus, the turbulent burning velocity may be varied with the Markstein number due to the thermo-diffusive effects.

On the other hand, burning velocity of ethane-air flames is not significantly affected by the thermo-diffusive effects due to the flame stretch because the Markstein number of ethane-air flames was around zero as shown in Fig. 5. Thus, the ratio $u_b / u_l$ is considered to depend not on the equivalence ratio, $\phi$ but only on $u' / u_l$, the relative turbulence intensity to the unstretched burning velocity of the flame.

3.3. Influence of turbulence on turbulent flame front

As flame front area may be dominant to the turbulent burning velocity, flame front properties were investigated. Fractal analysis(17) were applied to the tomograph images of the turbulent flames at $r_{sch} = 45$ mm. Box counting method was adopted in the analysis. Figures 9(a) and (b) show Fractal dimension, $D_3$ and inner cutoff scale, $\epsilon_i$, respectively. The Fractal dimension, $D_3$ of the flame front increased with the increase in the ratio of the turbulence intensity to the unstretched laminar burning velocity, $u' / u_l$. The inner cutoff scale, $\epsilon_i$ was around 0.8 mm in all cases.

Large Fractal dimension, $D_3$ at large $u' / u_l$ may be due to the small wrinkles convoluted on turbulent flame front as shown in Figs. 3. The flame front area might be increased by these wrinkling.

Here, as observed in these figures, the tomograph images are not coincide with the Schlieren image which is the integrated one along the light path. Boundary of the tomograph image seems inside of that of the Schlieren images in the case turbulence intensity, $u' = 2.46$ m/s. Some unburned region seem to get involved into the burned region.

The turbulent burning velocity related to the flame front area must be based on the mass consumption rate of unburned mixture rather than the entrainment rate to the flame front determined by the Schlieren images.

Another turbulent flame radius, $r_b$ based on the volume of the burned mixture was obtained from the pressure in the combustion chamber(18). At the timing of $r_{sch} = 45$ mm, this turbulent flame radius, $r_b$ is slightly smaller than $r_{sch}$ based on the Schlieren images with the increase in $u' / u_l$ as shown in Fig 10. Another turbulent burning velocity, $u_b$ is also obtained from $r_b$ at the timing of $r_{sch} = 45$ mm. As shown in Fig 11, this burning velocity $u_b$ based on the consumption rate of unburned mixture was slightly smaller than $u_b$ at larger $u' / u_l$ than 10. This burning velocity $u_b$ is directly related to the flame front area, although the disparity was small within $u' / u_l$ range examined in this study.

In order to investigate the flame front area from the flame

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**Fig. 9 Fractal properties of turbulent flames at $r_{sch}=45$ mm**

**Fig. 10 Flame radius based on burned gas volume, $r_b$**
morphology, perimeter of the flame tomograph image, \( \ell_{tgp} \) was examined in this study. The ratio of \( \ell_{tgp} \) to the perimeter of laminar flame whose burned gas volume is that of the corresponding turbulent flame, was considered to relate to the flame front area. Assuming the burned gas region is a sphere, its radius and perimeter are \( r_p \) and \( 2 \pi r_p \) respectively. Thus, the ratio \( \frac{\ell_{tgp}}{2 \pi r_p} \) may relate to the increase in the turbulent flame front area from the corresponding laminar one by turbulence.

As shown in Fig. 12, the ratio of the perimeter of turbulent to laminar flames, \( \frac{\ell_{tgp}}{2 \pi r_p} \), increased with the increase in the relative turbulence intensity to the flame, \( u'/u_1 \).

Figure 13 shows the ratio of the turbulent burning velocity based on the consumption rate of unburned mixture to the unstretched laminar burning velocity, \( \frac{u_p}{u_1} \). The ratio \( \frac{u_p}{u_1} \) increased with the increase in \( \frac{\ell_{tgp}}{2 \pi r_p} \). As shown in the figure, the perimeter of the turbulent flame measured in two-dimensional cross-sectional plane was found to correlate to the turbulent burning velocity.

On the other hand, turbulent burning velocity may be actually linked to the three-dimensional flame front area. Therefore, three-dimensional flame front area was considered from these two-dimensional information. Here, an expansion of the information on length to that of area was undertaken with a Fractal dimension because turbulent flame front has a Fractal nature as shown in Figs. 9. The ratio of the turbulent flame front area to the corresponding laminar flame front area was estimated as \( \left( \frac{\ell_{tgp}}{2 \pi r_p} \right)^2 \). Here, \( D_2 = D_3 - 1 \).

Figure 14 shows the examined correlation of the ratio of the turbulent burning velocity to the unstretched laminar burning velocity, \( \frac{u_p}{u_1} \) with the estimated ratio of the turbulent to the laminar flame front areas, \( \left( \frac{\ell_{tgp}}{2 \pi r_p} \right)^2 \). The ratio of the turbulent burning velocity to the unstretched laminar burning velocity, \( \frac{u_p}{u_1} \), was well correlated with \( \left( \frac{\ell_{tgp}}{2 \pi r_p} \right)^2 \).

4. Conclusions

Premixed turbulent flames are, in general, subjected to the thermo-diffusive effects in addition to the increase in the flame front area due to the influence of turbulence. In order to independently evaluate the effects of the increase in the flame front area on the burning velocity of turbulent flames, ethane-air laminar and turbulent flames were examined. Ethane flames have a Lewis number around unity and can therefore be considered insensitive to the thermo-diffusive effects. Flame front morphologic properties such as a Fractal dimension were obtained. Following results were obtained.

(1) Laminar burning velocity of ethane-air flames is not significantly affected by the flame stretch. The Markstein
number varied with the equivalence ratio, \( \phi \) but its value was around zero.

(2) The ratio of the turbulent burning velocity to the unstretched laminar burning velocity, \( u_\text{turb} / u_\text{l} \) was related to the magnitude of the ratio of the turbulence intensity to the unstretched laminar burning velocity, \( u'/u_\text{l} \). It did not depend on the equivalence ratio, \( \phi \) under the constant \( u'/u_\text{l} \).

(3) The turbulent burning velocity of ethane-air flames might not be significantly affected by the thermo-diffusive effects because the Markstein number was around zero. Flame front area might be dominant to the turbulent burning velocity.

(4) Fractal dimension, \( D_3 \) and perimeter, \( l_{gp} \) of the flame tomograph image increased with the increase in \( u'/u_\text{l} \). Increase in \( u'/u_\text{l} \) may increase the turbulent flame front area.

(5) Estimation of the increase in three-dimensional turbulent flame front area from laminar one was examined to \( (l_{gp}/2\pi r_\text{p})^2 D_3 = D_3 - 1 \) from the flame radius, \( r_\text{p} \) of laminar flame whose burned gas volume is that of the corresponding turbulent flame. The ratio of turbulent burning velocity based on the consumption rate of unburned mixture to the unstretched laminar burning velocity, \( u_\text{turb} / u_\text{l} \) was well correlated with \( (l_{gp}/2\pi r_\text{p})^2 \).

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