AN EXPERIMENTAL APPROACH TO VORTEX-FLAME INTERACTION USING COHERENT STRUCTURE IN A PREMIXED PLANE SHEAR LAYER

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ABSTRACT

The vortex-flame interaction is examined experimentally by using turbulent premixed flames propagating in the well-known plane shear layer. The shear layer is established between the higher- and lower-velocity mixture streams of 5.0 m/s and 2.5 m/s, respectively, and is acoustically excited by a speaker at a fundamental frequency of 452.5 Hz, in order to augment the periodicity of the organized eddy formation. A stoichiometric propane-air flame is stabilized behind a rod flame holder of 1 mm diameter, so that a rod-stabilized flame can propagate along the axes of organized eddies.

Optical observations using schlieren photography and velocity measurement using PTV are made on the rod-stabilized flame. The setting conditions of the shear layer indicate that turbulence generated is subdivided into the moderate one having a relatively large scale and a rather weak intensity. However, the proportionality constant between the enhancement rate of the burning velocity and the vortex strength exhibits a slight larger value of $(S_T/S_L)/(v_\theta/S_L) = 1.5$ than those obtained using a single vortex tube or a single vortex ring. It is found that the mutual interaction among neighboring eddies exerts non-negligible influence on the vortex-flame interaction.

INTRODUCTION

Recently much attention has been focused on the vortex bursting, since it constitutes one of the most probable enhancement mechanisms of the flame propagation velocity, and many models concerning the vortex bursting mechanism (Chomiak, 1976, Ishizuka, 1990, Hasegawa and Nishikado, 1996, Ashurst, 1996, Asato et al., 1997, Ishizuka et al., 1998) have been proposed on the basis of active experimental and numerical investigations. However, to simplify the numerical treatment and analysis, almost all models dealt with a single instantaneous combustion under simple flow configurations, such as a single vortex tube and a single vortex ring. This means that the proposed models do not take into account of the concrete information about the vortex-flame interaction under the practical and complicated combustion conditions, such as those in the internal combustion engines and gas turbine combustors, and therefore that they can not always be applied to the turbulent premixed flames formed under various kinds of complicated flow configurations.

In this investigation, to obtain the concrete and detailed information about the vortex-flame interaction under the practical flame conditions as far as possible, a turbulent premixed flame stabilized in the plane shear layer and propagating along the axes of a series of organized mixture eddies is optically observed and examined, and temporal processes of the vortex-flame interaction are analyzed. This is because that the shear layer is well known to be one of the most practical flame conditions (Ishino et al., 1993) and to be composed of a series of large scale organized eddies (Brown and Roshko, 1974). The shear layer employed in this investigation is formed between the higher- and lower-velocity mixture streams of 5.0 m/s and 2.5 m/s, respectively, and is acoustically excited by a speaker at a fundamental frequency of 452.5 Hz particular to the flow configurations of the shear layer, in order to enhance and improve the periodicity of the large scale eddy formation.

In this paper, a stoichiometric propane-air flame stabilized behind a rod flame holder of 1 mm diameter is focused and named the rod-stabilized flame. The rod axis is set along the boundary between two uniform mixture streams, so that the rod-stabilized flame can propagate along the axes of a series of vortex tubes formed in the shear layer. According to schlieren observation and velocity measurement using PTV, the appearances and behavior of the rod-stabilized flame propagating along the axes of organized eddies are discussed, by taking the characteristic length and velocity scales of the organized eddies into consideration.

In addition, the main advantages of the proposed technique are found in the practical merits that a stationary flame propagation can be simply realized in the shear layer without using any complicated devices, and that the continuous flame propagation enables longer time observations of the vortex-flame interaction under more practical flow configurations than those preceding investigations using a single vortex tube or ring.

EXPERIMENTAL APPARATUS AND METHOD

The schematic diagram of the apparatus is shown in Fig.1, and the structural details and dimensions of the measuring section of the open and vertical type premixed combustion tunnel are given in Fig.2, together with the coordinate axes used. Air supplied by a blower and propane supplied from a bomb (commercial grade gaseous propane of 96.4 % purity) are metered to form stoichiometric mixture and flow into the combustion tunnel, after being regulated and distributed into two definite flow rates for the higher- and lower-velocity streams. As shown in Fig.2, the exit section is divided by a splitter plate into two rectangular sections of 70 mm × 18 mm, from which two propane-air stoichiometric mixture streams having U_h = 5.0 m/s and U_l = 2.5 m/s are issued in the right- and the left-hand side sections, respectively. A wire gauze of #100 is installed in the exit section of the combustion tunnel to compensate the velocity defect in the velocity profile downstream of the splitter plate, as well as to prevent the flame from flashing back into the combustion tunnel.

A rod flame holder made of tungsten wire of 1 mm diameter is employed to stabilize a turbulent premixed flame in the shear layer. The rod is placed at the position (x, y, z : mm) = (-1, 18, 25) with the axis set parallel to the y-axis, as shown in Fig.2. The rod-stabilized flame is acoustically excited continuously at a natural frequency of f_0 = 452.5 Hz, using a loud-speaker installed in the contraction wall of the higher-velocity stream, so that the periodicity of the organized eddy formation can be dominated at the fundamental frequency, which is particular to the shear layer configurations employed.

Optical observation and velocity measurement are made for the rod-stabilized flame using schlieren photography and PTV, respectively. Instantaneous schlieren photographs are taken by using a conventional Z-configuration concave mirror system, combined with a Xenon flash lamp of 20 μs pulse width. Appearances and propagation characteristics of the turbulent premixed flame propagating in the shear layer are observed and discussed. In the velocity measurement, on the other hand, fine spherical plastic bubbles having a mean diameter of 50 μm and a mean density of 36 kg/m^3, called EXPANCEL as a registered name, are used as tracer particles. The amplitude responsibility of EXPANCEL particles to the sinusoidal flow oscillation at f_0 = 452.5 Hz is estimated to be more than 70 %. A continuous Xenon light source of an output of 75 W passes through an

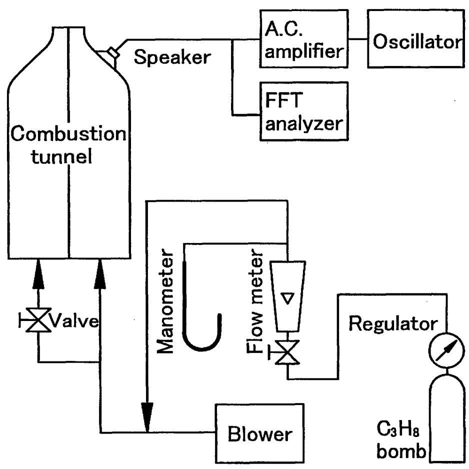


Figure 1 Schematic of the experimental apparatus

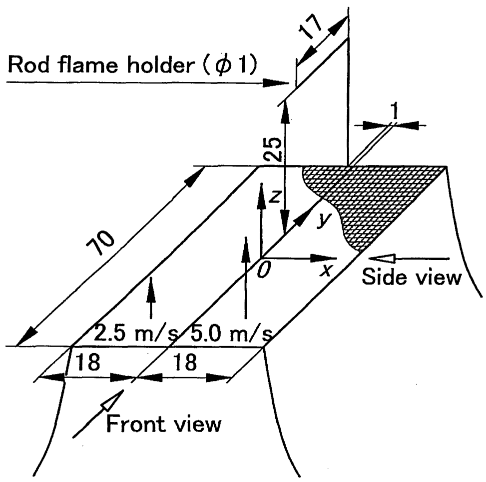


Figure 2 Structural details and dimensions of the open and vertical type combustion tunnel

optical system, consisting of a convex lens and a cylindrical lens, is shuttered mechanically at time intervals of 1 ms by a rotating disk with five rectangular notches on its periphery, and is focused into five consecutive pulsed light sheets of 5 mm width on the y-z plane containing the flame holder axis. Analyzing a lot of sets of five consecutive particle track images, the local flow information in the near flame region and the average burning velocity are estimated.

EXPERIMENTAL RESULTS

Cold Flow Properties without Combustion

An example of average velocity profiles across the x-y section at z = 25 mm is shown in Fig.3, where air is supplied instead of the propane-air mixture. Although, due to the velocity boundary layers developed on both sides of the splitter plate, a slight jetting and velocity defect are observed at both sides of the shear layer, it is found that the calming effect of a wire gauze installed in the exit section realizes a reasonable velocity distribution typical of the plane shear layer. Relative turbulence intensities of the higher- and lower-velocity streams are measured to be 1.5 % and 1.8 %, respectively.

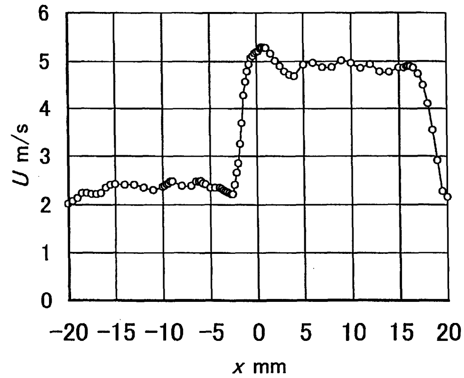


Figure 3 Average velocity profile across the x-y direction at z = 25 mm

Addition of propane to the lower-velocity air stream at a low flow rate of 3.0 *l*/min as a tracer makes possible schlieren observation of the coherent structure in the shear layer. An example of flash schlieren photographs is presented in Fig.4, where the left- and right-hand side arrows give the velocity vectors in the higher and lower uniform streams, respectively. Owing to the pronounced periodicity due to the acoustic excitation, a series of large scale organized eddies can be clearly observed in the shear layer and their spacings in the region of z = 25 ~ 60 mm, where the rod-stabilized flame propagates into the shear layer, are evaluated and averaged to be l_z = 8.5 mm. Taking the excitation frequency of f_0 = 452.5 Hz into account, the average convection velocity of organized eddies is calculated to be U_c = 3.8 m/s.

Structure and Behavior of Rod-Stabilized Flame

Instantaneous schlieren photographs of the rod-stabilized flame taken at an exposure time of 20 μs are shown in Fig. 5. Those instantaneous direct photographs taken at an exposure time of 0.25 ms are also shown in Fig.6. In each figure the left- and right-hand side pictures present the front view and the side view of the flames, which are taken simultaneously in the y-direction and from the x-direction, respectively. As indicated by two white vectors in the left-hand side pictures, the higher-velocity mixture flow is issued from the right section, while the lower-velocity mixture flow is issued from the left section. In Fig.7, an instantaneous direct photograph is also presented, which is specially taken at an exposure time of 0.5 ms from the direction given by an oblique arrow in the

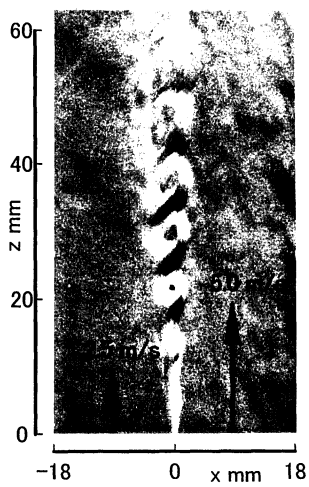


Figure 4 Appearances of a series of organized eddies in the plane shear layer

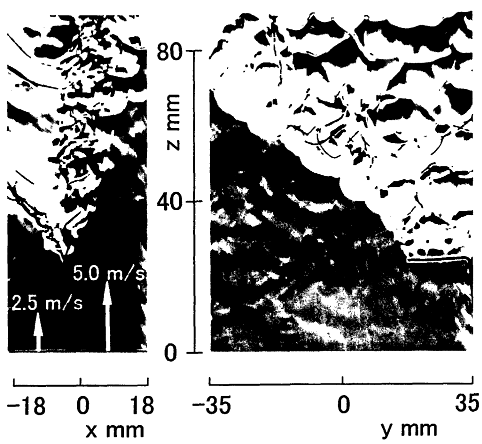
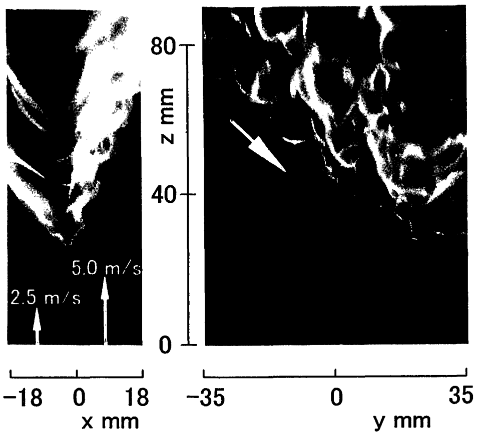


Figure 5 Instantaneous schlieren photographs of the flame taken at an exposure time of 20 μs



(a) Front view (b) Side view

Figure 6 Instantaneous direct photographs of the flame taken at an exposure time of 0.25 ms

Figure 7 Instantaneous direct photograph of the flame taken from the half left direction given by the oblique arrow in Fig. 6(a) at an exposure time 0.5 ms

side view of Fig. 6(b). The latter figure provides information where the rod-stabilized turbulent flame propagates and how it interacts with a series of organized eddies.

According to the schlieren photographs of Fig.5, the rod-stabilized turbulent flame appears to be composed of continuous wavy surface and is classified into the wrinkled laminar flame. As seen in the front views in Figs. 5(a) and 6(a), a relatively smooth wrinkled laminar combustion wave spreads obliquely over the lower velocity side at a large angle of inclination, whereas a rugged combustion wave inclines steeply into the higher velocity mixture stream with a small angle of inclination, resulting apparently in an inclined V-shaped flame. In the side views in Figs. 5(b) and 6(b), on the other hand, a wrinkled laminar flame propagates obliquely in the half left direction from the rod edge. Careful observation of the latter flame clarifies that it consists of a series of roundish flame elements, which protrude towards the unburnt region of the shear layer and parallel to the rod axis, and have approximately equal spacings of l_z = 8.4 mm to those of the organized eddies found in Fig. 4. As shown by a circle in Fig. 7, it is sure that the roundish wrinkled laminar flame is established exactly in the central region of the shear layer and interacts there with a series of organized eddies. These considerations mean that, therefore, quantitative measurements of the flow and flame conditions, such as the local inflowing mixture velocity just upstream of the flame surface and the inclination angle of the flame to the local mixture flow direction, enables quantitative estimation of the degree of vortex-flame interaction.

Measurement of Flame Propagation Velocities Using PTV

In this paper velocity measurement is made with PTV. In order to certify the validity of the proposed technique, the laminar burning velocity is first measured using a rod-stabilized laminar flame in the lower velocity uniform mixture stream. An example of PTV images is shown in Fig. 8(a), where the same rod flame holder is set at the central position of the lower velocity mixture stream, (x, y, z : mm) = (-9, 35, 25). A large number sets of five consecutive particle images can be clearly seen in the picture. By taking time intervals of the pulsed light sheets of 1.0 ms into account, the local uniform mixture velocity entering the flame surface is calculated to be U_L = 2.3 m/s, while the average incidence angle of the unburnt mixture flow to the flame surface is read to be θ_{ml} = 10.3 °. These values give the burning velocity as

$$S_L = U_L \sin\theta_{ml} = 0.41 \text{ m/s},$$

which gives a quite reasonable value for the stoichiometric propane-air mixture (Fristrom, 1995).

An example of PTV images taken for the rod-stabilized turbulent flame in the shear layer is given in Fig. 8(b), for which the same picture processing is carried out. In this case, however, uncertainty due to the eddying motion of organized eddies in the thick pulsed light sheet of 5 mm, which is nearly equal to the average diameter of organized eddies of l_d = 5.4 mm, is unavoidable in the local velocity measurement. The mean convection velocity of organized eddies of U_c = 3.8 m/s is then employed, instead of the local unburnt mixture velocity just upstream of the flame surface. Detailed picture processing of Fig. 8(b) also shows that the intersection angle of the local unburnt mixture flow with the flame surface varies widely from a minimum of 19° to a maximum of 38°. Taking a simple average of 19° and 38° yields the intersection angle of θ_{mt} = 28.5°. The average turbulent burning velocity of the rod-stabilized flame in the shear layer is therefore finally calculated to be

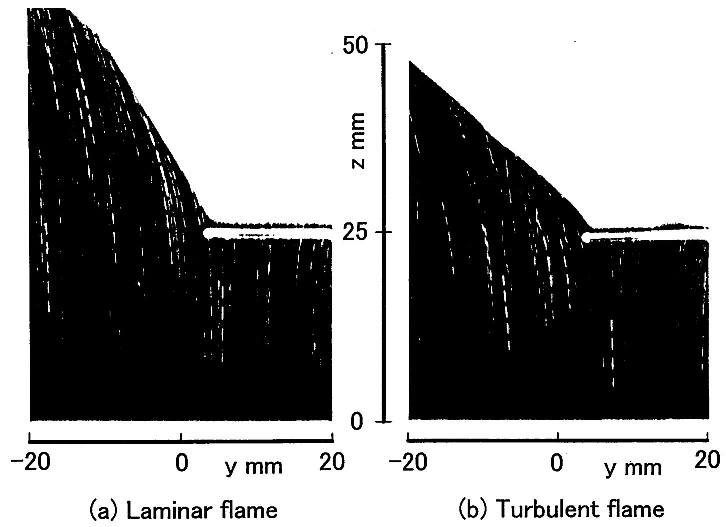


Figure 8 Examples of PTV images

$$S_T = U_c \sin\theta_{mt} = 1.8 \text{ m/s}.$$

As a result, the interaction of the laminar combustion wave with a series of organized eddies under the flow conditions and configurations employed in this investigation is quantitatively concluded to enhance the burning velocity more than four times as large as the laminar burning velocity, $S_T/S_L = 4.4$.

Brief Discussion on the Vortex-Flame Interaction in the Plane Shear Layer

In order to make quantitative considerations of the vortex-flame interaction effective and reasonable, it is necessary to obtain the concrete information about the vortex characteristics, such as the tangential velocity, the vortex diameter, the circulation and the vortex strength. Based on the flow setting conditions of the shear layer employed here, the tangential velocity is approximately calculated to be

$$v_\theta = (U_h - U_l)/2 = 1.25 \text{ m/s}.$$

According to the picture processing of Fig.4, the average characteristic diameter is measured to be l_d = 5.4 mm within the flow range of z = 25 ~ 60 mm. The circulation is then calculated to be

$$\Gamma = \pi l_d v_\theta = 2.1\times10^{-2} \text{ m}^2\text{/s}.$$

The vortex strength, which is a non-dimensional vortex parameter and defined by a ratio of the tangential velocity to the laminar burning velocity, is given as v_θ/S_L = 3.0. Another important dimensionless vortex parameter should be introduced, which is defined by a ratio of the characteristic vortex length scale to the laminar flame thickness, l_d/δ_L, and gives a measure of the vortex length scale. The latter, called here the vortex scale, is evaluated to be l_d/δ_L = 18, by assuming the laminar flame thickness to be δ_L = 0.3 mm. In Table 1, these values are summarized, together with the average convection velocity of organized eddies, U_c = 3.8 m/s.

The flame characteristics, such as the laminar burning velocity of the stoichiometric propane-air mixture S_L, the turbulent burning velocity S_T, and the enhancement rate of the burning velocity S_T/S_L, are also tabulated in Table 2, based on the experimental results. Taking into consideration that, as the dimensionless vortex parameters in Table 1 suggest, the flow conditions of the shear layer employed here are not so high, but rather moderate, and that the rod-stabilized flame is classified into the wrinkled laminar flame, the enhancement rate of S_T/S_L = 4.4 provides a quite reasonable value for explaining the degree of the vortex-flame interaction in the shear layer.

Finally, parameters necessary for estimating the enhancement rate of the flame propagation velocity by using the vortex-bursting mechanism are evaluated, based on the experimental data obtained. The enhancement effects are generally expressed in the S_F ~ v_θ diagram (Asato et al., 1997, Ishizuka et al., 1998), where S_F indicates the flame velocity and includes the expansion velocity due to exothermic reaction. It is convenient and fundamental, however, to figure it in the non-dimensional diagram, S_F/S_L ~ v_θ/S_L, in order to enable wide and universal comparison among data obtained with different fuels and different flame configurations. Since the flame velocity is not measured in this investigation, the dimensionless turbulent burning velocity S_T/S_L, which excludes the expansion velocity, is used instead of S_F/S_L. According to values in Tables 1 and 2, the proportionality constant between the dimensionless turbulent burning velocity, S_T/S_L, and the vortex strength, v_θ/S_L, is calculated to be

$$(S_T/S_L)/(v_\theta/S_L) = 1.5.$$

This exhibits a slight larger value than those reported in references (Chomiak, 1976, Ishizuka, 1990, Ashurst, 1996, Hasegawa and Nishikado, 1996, Asato et al., 1997, Ishizuka et al., 1998) by about 50%, even if it does not include the effect of thermal expansion due to combustion. It is concluded at this point that, in spite of the moderate turbulence conditions having a relatively large scale and a rather weak turbulence intensity, the influence of the mutual interaction among neighboring vortex tubes on the vortex-bursting is not negligible at all, but it promotes and activates the enhancement process of flame propagation velocity by the vortex-bursting mechanism.

Table 1 Summary of the Vortex Conditions of Organized Eddies in the Plane Shear Layer

Tangential velocity v_θ [m/s]	Average diameter l_d [mm]	Circulation Γ [m^2/s]	Vortex strength v_θ/S_L	Vortex scale l_d/δ_L	Average convection Velocity U_c [m/s]
1.25	5.4	2.1×10^{-2}	3.0	18	3.8

Table 2 Summary of the Flame Characteristics of the Rod-Stabilized Flame

Laminar burning velocity S_L [m/s]	Turbulent burning velocity S_T [m/s]	Enhancement rate S_T/S_L	Degree of interaction $(S_T/S_L)/(v_\theta/S_L)$
0.41	1.8	4.4	1.5

CONCLUSIONS

In this paper turbulent premixed flames propagating continuously along the axes of organized eddies in the shear layer are optically observed and analyzed, using schlieren photography and PTV technique. Detailed observation of instantaneous schlieren photographs and detailed picture processing of PTV images are made on the rod-stabilized flame. The results obtained are summarized as follows.

(1) Turbulent premixed flame stabilized in the shear layer consists of a continuous series of roundish and wrinkled flame elements, which protrude toward the unburnt region of the shear layer at approximately same spacings as those of the organized eddies. This suggests that the roundish wrinkled laminar combustion wave results from the intimate interaction with a series of organized eddies.

(2) The tangential velocity and the average diameter of organized eddies in the shear layer are estimated to be v_θ = 1.25 m/s and l_d = 5.4 mm, respectively. These values give two dimensionless vortex parameters, one is the vortex strength; v_θ/S_L = 3.0 and the other is the vortex scale; l_d/δ_L = 18, indicating that the turbulence conditions employed here is subdivided into the moderate turbulence.

(3) According to velocity measurement using PTV, the laminar burning velocity of the stoichiometric propane-air mixture is estimated to be 0.41 m/s, while the average turbulent burning velocity is measured to be 1.8 m/s. As a result, the enhancement rate of the burning velocity due to the vortex-flame interaction in the shear layer is calculated to be S_T/S_L = 4.4, which is considered to be quite reasonable from the viewpoint of the wrinkled laminar flame model of turbulent premixed combustion.

(4) Calculation of the ratio of the non-dimensional turbulent burning velocity to the vortex strength gives $(S_T/S_L)/(v_\theta/S_L)$ = 1.5, being a slight larger value than those already reported by about 50 %, even though it does not include the effect of thermal expansion due to combustion. This fact strongly suggests non-negligible but relatively intense influences of the mutual interaction among neighboring vortices on the enhancement mechanism of flame propagation by the vortex-bursting phenomenon.

Finally, in order to elucidate quantitatively the influences of the intimate interaction among neighboring vortices on the vortex-bursting phenomenon, more systematic and detailed observation and measurement are necessary under higher and more intense flow and vortex conditions of the shear layer than those employed in this paper.

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