Investigation of Flamelets in a Turbulent Premixed Flame With a 4-Element Electrostatic Probe and a 2-D LDV

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NTRODUCTION

There has been interest in flamelets in turbulent premixed flames ever since the early work of Karlovitz[(1)]. Klimov[(2)] showed that in turbulent flows at sufficiently high Reynolds numbers, the strain field promotes locally planar flamelets that may be influenced by flame stretch, lessening influences of flamelet curvature. In the reaction-sheet or "flamelet" regime of premixed turbulent combustion, the flamelets may be treated in a first approximation as unaffected internally by the turbulence and as propagating into the reactant gas at the laminar burning velocity S_u[(3)]. The turbulent flame structure then depends on the statistical distribution of these flamelets through the turbulent flame brush. Because of experimental difficulties, very few measurements of statistics of flamelets in turbulent premixed flames have been reported. The overall objective of the present work is to obtain statistical information about the flamelets in turbulent flames by use of electrostatic probes and LDV (laser doppler velocimeter) and to ascertain modifications of internal flamelet structure by turbulence.

The electrostatic probe was introduced by Suzuki and Hirano[(4)] as a means of investigating flamelets in turbulent flames. These probes can provide information on planar flamelet motion or on flamelet curvature, depending on which is dominant and on the manner of data analysis. In the present experiments, the average radius of curvature of the flamelets is about 4 mm[(5)], and the size of the volume probed by the detection system is about 1 mm, so that effects of flamelet curvature are small and are neglected. A drawback of previous measurements of locally planar flamelets in turbulent flames by electrostatic probes is that only three electrodes were employed. This allows measurement of flamelet motion only in a plane defined by the electrodes and fails to provide information on flamelet velocity components normal to this plane. Unmodified planar flamelets therefore may exhibit velocity components with respect to the gas in this plane that are greater than or less than S_u, depending on the flamelet orientation[(6)]. The present work avoids this objection by using four elements, the ultimate number, for the first time.

Ambiguity is eliminated in the present work by the four-element electrostatic probe with electrodes arranged in a tetrahedral configuration so that all three components of the velocity of motion of a locally planar flamelet can be measured. These measurements provide information on the magnitude of the velocity of motion of the flamelets as well as on the orientation of the flamelet sheet. This information is relevant to the structure of the turbulent flame. In addition, coupled with a simultaneous LDV measurement of gas velocity, the component of the burning velocity with respect to the gas can be obtained in the plane of the LDV. This provides most of the desired information, lacking only the third component of the burning velocity, which would require a 3-D LDV for its measurement, an instrument that unfortunately is not yet available to us.

Results are reported here on measurements of a propane-air flame with equivalence ratio 1.10, corresponding to a laminar burning velocity of 0.45 m/s[(6)]. The turbulent mixture is supplied through a cylindrical burner 26 mm in diameter at an average velocity of 4.0 m/s, with fully developed pipe flow from the burner tube at a Reynolds number of about 10,000, giving an average turbulence intensity of about 0.33 m/s. The Kolmogorov scale estimated from hot-wire measurements in cold flow is about 240 µm, compared with a calculated laminar flame thickness of roughly 100 µm. These conditions place the flame theoretically in the flamelet regime, without broken flamelets, but not in the weak-turbulence limit, so interesting effects might be observed. The measurements were made at a distance 32 mm above the burner exist and 4 mm from the centerline. This position was selected as that of approximately the maximum flamelet-passing frequency[6], to facilitate rapid data acquisition

EXPERIMENTAL

The LDV system employs a 1.0 W argon ion laser operating with multiple lines, a two-color four-beam forward-scattering optical arrangement and a Doppler signal analyzer for the measurement of instantaneous axial and radial components (with z vertical and x horizontal) of the local gas-velocity vector **U**. SiO_2 powder was used as the scattering par-

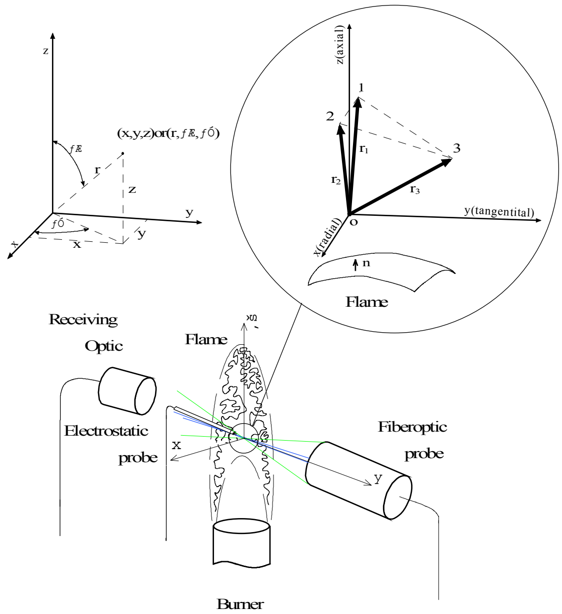

Fig. 1 Simultaneous measurement of the local gas velocity and the flame front movement

ticles that were seeded in the unburnt mixture stream.

The electrostatic probe adopted for the measurement of the local velocity vector **V** of the flamelet was composed of a four-element complex, sensors Nos. 0, 1, 2 and 3. In the electrostatic probe, the wire axes of the four sensors were parallel and about 1 mm apart, the sensor tips being in a tetrahedral configuration. Sensors Nos. 0, 1 and 2 form a vertical plane, which contains the burner axis (with z vertical) and the radial direction (with x horizontal). As shown in Fig. 1, the electrostatic probe was installed horizontally from the tangential direction (with y horizontal), and the wire axis of each sensor was parallel to the LDV optical axis. The midpoint of the lowest sensor, sensor No. 0, was 0.5 mm above the center of the LDV measuring volume. Each sensor of the electrostatic probe was formed from a platinum wire of 0.1 mm diameter, 0.5 mm long. The sensor projected from a finely drawn quartz tube which provide electrical insulation, over which a water-cooled brass tube was fitted. The sensor potential of the electrostatic probe with respect to the burner was kept at -12 V.

THE FLAMELET VELOCITY VECTOR

The process for determining the local flamelet velocity vector **V** can be discussed by referring to aspects of the flame front passing the electrostatic probe, illustrated in Fig. 1. In the figure, the directions x, y and z represent the radial, tangential and axial directions of the burner, respectively. Define a unit vector **n** normal to the flame front in the direction of flamelet motion as

$$\mathbf{n} = \alpha\mathbf{i} + \beta\mathbf{j} + \gamma\mathbf{k} \quad (1)$$

$$\alpha = \sin\theta\cos\varphi,\ \beta = \sin\theta\sin\varphi,\ \gamma = \cos\theta \quad (2)$$

where **i**, **j** and **k** represent unit vectors in the x, y and z directions, respectively, and θ and φrepresent polar and azimuthal angles, respectively. The x-z plane contains the axis of the burner (with z vertical) and is the plane in which the LDV measures the gas velocity component.

The four sensors of the electrostatic probes ideally are arranged in a tetrahedral configuration. The sensor No. 0 is on the origin at the bottom, sensors Nos. 0, 1 and 2 are vertically positioned on the x-z plane, and sensor No. 3 is on the y-z plane. The position vectors $\mathbf{r}_1$, $\mathbf{r}_2$ and $\mathbf{r}_3$ of the sensors Nos. 1, 2 and 3 with respect to sensor No. 0 are

$$\mathbf{r}_1 = \frac{1}{2} l\,\mathbf{i} + \frac{\sqrt{3}}{2} l\,\mathbf{k} \quad (3)$$

$$\mathbf{r}_2 = -\frac{1}{2} l\,\mathbf{i} + \frac{\sqrt{3}}{2} l\,\mathbf{k} \quad (4)$$

$$\mathbf{r}_3 = \sqrt{\frac{2}{3}}\, l\,\mathbf{j} + \frac{1}{\sqrt{3}} l\,\mathbf{k} \quad (5)$$

where l represents the distance between sensors. The distances l_1, l_2 and l_3 for flame travel from sensor No. 0 to sensors Nos. 1, 2 and 3 are

$$l_1 = \mathbf{r}_1 \cdot \mathbf{n} = V\tau_1 \quad (6)$$
$$l_2 = \mathbf{r}_2 \cdot \mathbf{n} = V\tau_2 \quad (7)$$
$$l_3 = \mathbf{r}_3 \cdot \mathbf{n} = V\tau_3 \quad (8)$$

whereτ_1, τ_2 and τ_3 represent the periods from the time when a peak of the ion current j_0 was detected by the sensor No. 0 to the times when the peaks of the ion currents j_1, j_2 and j_3 were detected by sensors Nos. 1, 2 and 3, respectively. From Eqs.(3) - (5) and Eqs.(6) - (8), the magnitude V of the local flame-front-velocity vector can be obtained as

$$V = \frac{\sqrt{6}l}{\sqrt{9(\tau_1^2+\tau_2^2+\tau_3^2)-6(\tau_1\tau_2+\tau_2\tau_3+\tau_3\tau_1)}} \quad (9)$$

The orientation of the vector **n** has the direction cosines

$$\alpha = \frac{\sqrt{6}(\tau_1-\tau_2)}{\sqrt{9(\tau_1^2+\tau_2^2+\tau_3^2)-6(\tau_1\tau_2+\tau_2\tau_3+\tau_3\tau_1)}} \quad (10)$$

$$\beta = \frac{3\tau_3-\tau_1-\tau_2}{\sqrt{9(\tau_1^2+\tau_2^2+\tau_3^2)-6(\tau_1\tau_2+\tau_2\tau_3+\tau_3\tau_1)}} \quad (11)$$

$$\gamma = \frac{2(\tau_1+\tau_2)}{\sqrt{9(\tau_1^2+\tau_2^2+\tau_3^2)-6(\tau_1\tau_2+\tau_2\tau_3+\tau_3\tau_1)}} \quad (12)$$

with respect to the x, y and z axes, respectively. Therefore, the local flamelet velocity vector **V** is

$$\mathbf{V} = V(\alpha\mathbf{i} + \beta\mathbf{j} + \gamma\mathbf{k}) = V_x\,\mathbf{i} + V_y\,\mathbf{j} + V_z\,\mathbf{k} \quad (13)$$

THE COMPONENT of the BURNING VELOCITY VECTOR in the x-z PLANE

The component S of the burning-velocity vector of a flamelet in the x-z plane can be obtained geometrically from **U** and **V**. With the definition $\mathbf{V} = \mathbf{V}_{xy} + V_z\mathbf{k}$, $\mathbf{V}_{xz}$ is the sum of **S** and the component of **U** normal to the flame front. Thus,

$$\mathbf{S} = \mathbf{V}_{xz} - \frac{\mathbf{V}_{xz} \bullet \mathbf{U}}{V_{xz}}\,\mathbf{e}_v \quad (14)$$

where V_{xz} is the magnitude of $\mathbf{V}_{xz}$ and $\mathbf{e}_v$ represents a unit vector in the direction of $\mathbf{V}_{xz}$. Since the ion current is maximum approximately where the rate of heat release is maximum, the magnitude of S for a planar undisturbed laminar flame will lie between unburnt-gas and burnt-gas burning velocities, closer to the latter with sufficiently fine spatial LDV resolution but closer to the former in the present experiments.

RESULTS and DISCUSSIONS

If the velocity fluctuation is recorded at the same time that the flame front passes the probe, then **U** and **V** are measured simultaneously. Figure 2 shows the resulting projections of the velocity vectors of flamelet motion on the x-z, y-z and x-y planes. Each point in the figure is the tip of an arrow from the origin representing the velocity component. The first of these figures (the projection into the x-z plane) is quite similar to a figure obtained previously[6] from measurements with the three-element electrostatic probe at the same position in the same flame, indicating excellent reproducibility of the technique. It shows that the flame motion is always upward and skewed slightly in the direction outward from the centerline, as would be expected in this configuration. The other two figures show a fairly symmetric direction about zero in the y direction, as anticipated from the symmetry of the experiment

The LDV measurements are shown in Fig. 3, in the same format as Fig. 3. These results also are quite similar to those reported earlier[6] where it is explained that the distribution around the direction away from the burner axis is a consequence of the average thermal expansion between the centerline and the measurement point. From these results and those of Fig. 2, it is possible to obtain the x and z components of the burning velocity, **S** of Eq. (14), shown in Fig. 4. A number of different observations can be made from Fig. 4.

First, it may be noted that the vector distribution in Fig. 4 is asymmetric, with the S_x axis excluded. This exclusion is much less pronounced than that found with three-element probe[6], which gave velocities predominantly in the positive and negative S_z directions, but it still is quite evident. If the exclusion were associated with interference effects of probe leads, then there should be asymmetries in the x and y direction-cosine distributions α and β which are not observed. It therefore appears that the asymmetry implies that at the measurement position in the turbulent flame brush the flamelets propagate primarily vertically and never solely in the radial direction.

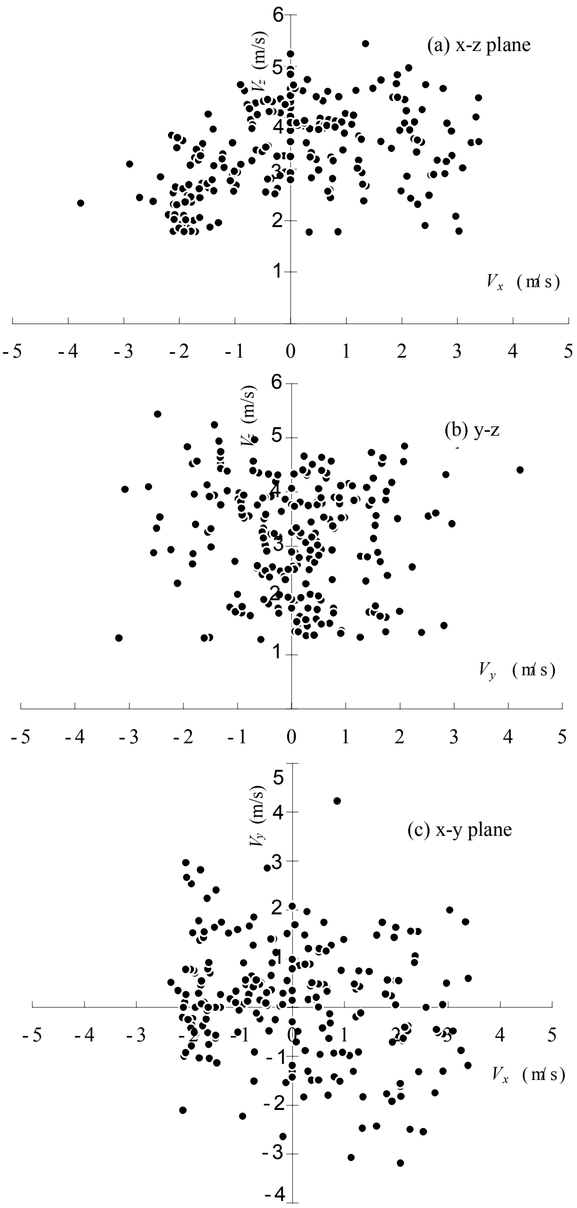

Fig. 2 A vector distribution map of the local flame-front velocity in (a) the x-z plane, (b) the y-z plane and (c) the x-y plane

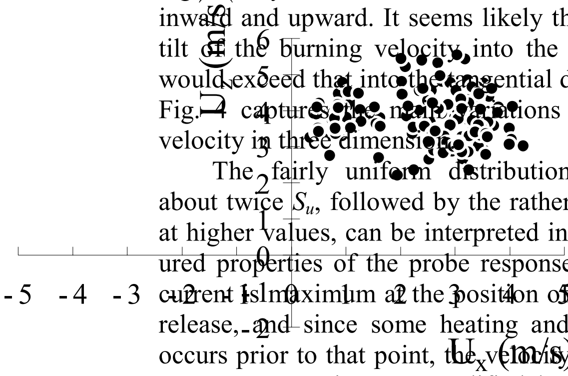

Fig. 3 A vector distribution map of the local gas velocity component in the x-z plane

There is roughly equal distribution of positive and negative values of S_z in Fig. 4. This does not correspond to negative burning velocities. The ion-probe traces distinguish the unburnt and burnt sides of the reaction front, and in all cases in Fig. 4 the flamelet is found to be propagating with respect to the gas into the unburnt mixture. For a steady, horizontal laminar flame in a uniform vertical flow, S_z is negative in Fig. 4, and the results thus indicate that the reactants are above the flamelet sheet about as often as they are below it at the measurement position in this turbulent flow. Fluctuations in the propagation direction extend to angles of about $\pi/4$ with respect to the x axis. The largest burning velocities are found for flames moving radially outward and downward into reactants or inward and upward. It seems likely that the extent of tilt of the burning velocity into the radial direction would exceed that into the tangential direction, so that Fig. 4 captures the main variations of the burning velocity in three dimensions.

The fairly uniform distribution up to values about twice S_u, followed by the rather sharp decrease at higher values, can be interpreted in terms of measured properties of the probe response. Since the ion current is maximum at the position of maximum heat release, and since some heating and gas expansion occurs prior to that point, the velocity that the instrument measures in an unmodified laminar flame lies between S_u and S_b, the laminar burning velocity in the burnt gas. Because of effects of flow divergence, this latter velocity is found experimentally to be on the order of 2 m/s or somewhat less[9]. A hypothesis

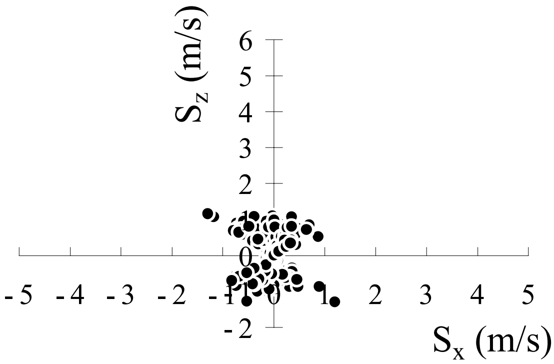

Fig. 4 A vector distribution map of the component in the x-z plane of the local velocity of the flamelet with respect to the gas

consistent with the present observations is that, in the flame measured here, when flamelets are uninfluenced by strain the instrument reads a burning velocity of about $2S_u$, roughly 1 m/s. The smaller values of the magnitude of **S** then correspond either to there being a component of the burning velocity in the y direction or to a reduction in the burning velocity through flamelet stretch, to be expected if the instrument is measuring velocity in the downstream part of the laminar flamelet structure. The few examples of large burning velocities might then correspond to flamelets experiencing compression (negative stretch) or to small positive stretch with Lewis number less than unity, the limiting-reactant (oxygen) diffusivity exceeding thermal diffusivity for this equivalence ratio, leading to an increased rate of heat release per unit flamelet area under small stretch. It seems unlikely that all of the distribution towards zero is attributable to the y component of the burning velocity, that is, apparently stretch reduces the burning velocities of a number of flamelets, as has been predicted[2].

CONCLUSIONS

To investigate changes in burning velocities of flamelet in a turbulent premixed flame, efforts have been placed on measuring the component of the local motion vector of the flamelet with respect to gas in a vertical plane above the burner. The major results obtained in the present study are as follows:

The projections of the local motion vectors of the flamelets with respect to gas, at the measurement point are distributed over practically all directions, excluding purely tangential directions. Components of burning velocities in a vertical plane through the burner axis range in magnitude from nearly zero to a few times the planar, unstrained adiabatic laminar burning velocity S_u, at the measurement point of the present experiment. It may be concluded from these measurements that turbulence exerts influences on the flamelets and causes at least some of them to exhibit increased burning velocity and probably others to exhibit decreased burning velocity, defined in terms of the velocity at the position of maximum heat release.

REFERENCES

1. Karlovitz B., et al, Proc. Comb. Institute 4: 613-620 (1953)
2. Klimov A. M., Zh. Prikl. Mekh. Fiz. 3: pp. 49-58 (1963)
3. Libby P..A and Williams F. A., eds., Turbulent Reacting Flows, Academic Press London, 1994
4. Suzuki T., and Hirano T., Proc. Comb. Institute 20: 437-444 (1984)
5. Furukawa J., et al, Combust. Flame 112: 293-301 (1998)
6. Furukawa J., et al, Combust. Flame 113: 487-491 (1998)
7. Furukawa J., et al, JSME Int. Jour. B36-4: 682-687 (1993)
8. Furukawa J., and Hirano T., Proc. Comb. Institute 25: 1233-1239 (1994)
9. Furukawa J., et al, Combust. Science Technol. 154: 163-178 (2000)