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Turbulent burning velocity measurements: Extended to extreme levels of turbulence

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Abstract

Previous measurements of turbulent burning velocity (S_T) have been reported by Gülder and colleagues for *intense* levels of turbulence, defined to be u'/S_L values between 12 and 24, and normalized integral scales (L_x/δ_L) up to 46. The present work extends burning velocity measurements to much higher levels of turbulence than have been considered before: to *extreme turbulence* defined as u'/S_L values from 25 to 163 and L_x/δ_L up to 114. These conditions are argued to be more representative of the turbulence found in certain engines. To do so, a new large, piloted Bunsen burner (called Hi-Pilot) was developed and OH and formaldehyde PLIF images provided the time-averaged contours of progress variable based on OH (c_{OH}). The conventional global consumption speed ($S_{T,GC,1}/S_L$) is based on the $c_{OH} = 0.5$ contour and it was found to exceed 25. Two other measured speeds are based on the leading edge ($S_{T,GC,2}$) and the component due to flamelet surface density ($S_{T,F}$). Varying the integral scale had a significant effect on $S_{T,GC,2}$ but not on the other two burning velocities. The consumption speed $S_{T,GC,1}$ curve displayed "bending" in the range of extreme turbulence, while the flamelet surface density contribution ($S_{T,F}$) curve instead flattened out and was independent of turbulence intensity. A possible explanation for these measured trends is based on the observed extensive broadening of the preheat zone. Preheat broadening depends on the integral scale and is believed to attenuate the turbulence that eventually interacts with the reaction zone. Results indicate a breakdown of the laminar flamelet assumption; it appears that preheat broadening may cause thermal diffusivity to dominate over the flame wrinkling mechanism.

Keywords: Turbulent combustion; Burning velocity; OH-PLIF

1. Introduction

The turbulent burning velocity (S_T) is one metric that is commonly used to compare different experiments and simulations of premixed turbulent flames [1]. However, disagreements have arisen because it has several different definitions. Furthermore, although values of S_T can be correlated if the experiments have the same general flame geometry [1] (such as a Bunsen geometry), attempts to correlate data from Bunsen, spherical and counter-flow flames have not been successful.

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A research question is: how does S_T scale with turbulence level and integral scale when the values of these two parameters are increased by a factor of six above the largest values previously achieved? Information about the flame structure and burning velocity within extreme turbulence is needed to improve numerical simulations, including those of Sankaran et al. [2], Sundaram et al. [3], Huh et al. [4], and Lee and Huh [5]. Kariuki [6] studied burning velocity for complex geometries, while Gülder has performed extensive work on Bunsen geometries.

Gülder and colleagues [7–10] measured S_T for the largest values of u'/S_L that had been achieved for Bunsen-type flames prior to the present study; their values ranged between 12 and 24, which is defined as *intense turbulence*. Their integral scale (L_x) ranged from 0.5 to 3 mm, and when normalized by flame thickness was as large as 46. The present work extends the previous database by measuring turbulent burning velocity, as well as brush thickness and flame surface density, in the new range of u'/S_L from 25 to 163, which is defined here to be *extreme turbulence*. Longitudinal integral scale was varied from 6 to 41 mm, and when normalized by the preheat zone thickness ($L_x/\delta_{PHZ,L}$) values as large as 114 were achieved. This extreme turbulence is argued to be more representative of certain engine conditions. Gülder [7], Gülder and Smallwood [8], Andrews et al. [11], Bradley et al. [12,14,15] and Abdel-Gayed and Bradley [13] observed that large turbulence levels caused their burning velocity curves to display a 'bending' effect. They also observed that increasing the integral scale increased S_T. Both studies found that an improved correlation occurs if S_T/S_L is plotted against the turbulent Reynolds number ($Re_T = u'L_x/\nu$). The thickness of the preheat zone is another relevant parameter since it indicates the degree of turbulent diffusion upstream of the reaction layer. The preheat thicknesses of the present flames are reported in a separate paper [16] and are used here to help explain some of the observations. Correlations between turbulent flame speed and the aforementioned variables are an objective of this work.

2. Experiment details

The Hi-Pilot is a highly turbulent, premixed, axisymmetric burner that stabilizes a 21.6 mm diameter central Bunsen flame. Premixed reactants are composed of methane–air at an equivalence ratio $\varphi=0.75$. The central flame is surrounded by a 108 mm co-flow of hot products produced by the same methane–air mixture (see Fig. 1). Further burner details are found in Ref. [16].

Run conditions are listed in Table 1; they were obtained by using slotted plates, a converging plenum [16], and a mean centerline velocity as large as 89 m/s. To normalize the data, values of laminar flame speed (S_L) and preheat thickness ($\delta_{PHZ,L}$) were determined from CHEMKIN to be 23.2 cm/s and 0.36 mm, respectively.

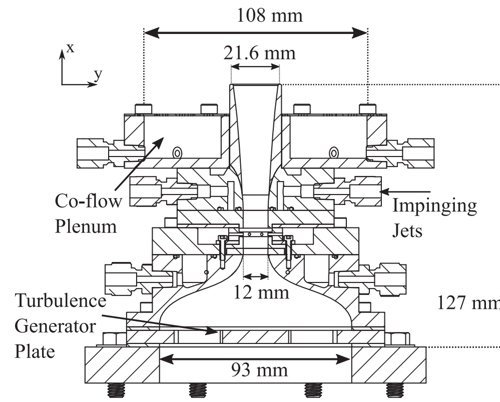

Fig. 1. Schematic of the Michigan Hi-Pilot burner.

2.1. Characterization of turbulence and flame boundary

Hotwire anemometer measurements showed that u' varied by less than 15% across the central 80% of the burner exit with no flame present. Laser Doppler Velocimetry (LDV) was used [16] to measure centerline values of mean velocity, u', and integral scale, as listed in Table 1. Taylor's frozen flow hypothesis (which assumes a linear transformation between the temporal and spatial autocorrelations) has often been applied in the literature to determine integral length scales from single point measurements, even at very large turbulence levels. However, as the turbulence intensity becomes large Taylor's approximation becomes invalid. Since u'/U_0 exceeds 30% for many conditions studied here, a correction [17–23] was applied that relates the length scale based on Taylor's frozen flow hypothesis $L_{x,FR}$ to the true integral scale L_x:

$$L_x = L_{x,FR}(1 + 5(u'/U_0)^2)^{1/2} \quad (1)$$

For a typical u'/U_0 of 35%, the correction causes a 27% increase in integral scale. This correction was applied, however none of the conclusions of the work are changed if it were not.

A comment is required regarding the size of our longitudinal integral length scales, which in some cases approach twice the burner exit diameter. It is well-established that the longitudinal integral scale can exceed ten times the lateral integral scale when a high contraction ratio nozzle is used. Tennekes and Lumley [24] examined the conservation equations and showed that vortex stretching occurs when a strong axial velocity gradient exerts a strain rate that elongates eddies in the flow direction. The vortex stretching mechanism has been explained by