



Evolution of turbulence through a broadened preheat zone in a premixed piloted Bunsen flame from conditionally-averaged velocity measurements



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ABSTRACT

This work assesses two hypotheses that predict how turbulence properties vary within premixed turbulent flames that lie in the regime of Broadened Preheat-Thin Reaction layers. There have been few prior measurements describing flames in this regime. The authors previously found that very broad preheat layers were achieved for turbulence levels (u'/S_L) up to 243. Surprisingly, the reaction layer thickness did not increase, despite having Kolmogorov scales smaller than the laminar reaction layer thickness. A first hypothesis is that the turbulence decays in the preheat layer (as the temperature rises and viscous forces increase), so that the reaction layer sees only a small fraction of the initial turbulence. It follows that this turbulence decay might be responsible for the observed non-linear bending of the curve of turbulent burning velocity versus turbulence level. A second hypothesis is that the total turbulent kinetic energy does not decrease significantly in the preheat zone; instead, the small eddies decay and cause the integral scale to increase. Conditional averages are required to assess these two hypotheses. Fluorescence imaging identified the reaction zone boundary and particle image velocimetry diagnostics were applied simultaneously. The velocity measurements were conditioned on η , the distance to the upstream boundary of the reaction zone in each image. Conditioned measurements of turbulent kinetic energy, average eddy rotational velocity, strain rate, enstrophy, and integral length scale were computed through the flame. Results indicate that the turbulence level does not decrease within the broad preheat layers, and therefore the first hypothesis is not valid. In fact, the turbulence level within the entire burner core does not vary appreciably. However, the second hypothesis was supported by the measurements, since the integral scale increased by 50% across the preheat layer. The total turbulent kinetic energy did not decrease significantly. One explanation for this result is that small eddies are dissipated in the preheat zone.

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1. Introduction

1.1. Motivation

While there have been many studies of the structure of premixed turbulent flames in the wrinkled flamelet regime [1–10] there have been relatively few studies in the regime of broadened preheat layers [11–22]. Previously, the measurements shown in Fig. 1a and b were reported by the present authors [16,17] for premixed flames in the Broadened Preheat-Thin Reaction layers (BP-TR) regime. To achieve broadened preheat layers, the turbulence intensity (u'/S_L , where u' is the root-mean-square of velocity fluctuations and S_L is the unstretched laminar burning velocity

locity) was varied up to 243 in a specially-designed large diameter piloted Bunsen burner. Several run conditions fell in the predicted regime of broken reaction layers [23–26] with turbulent Karlovitz numbers exceeding 100. The Kolmogorov scales of the most turbulent run conditions were approximately 30 μm , which is small relative to the laminar reaction layer thicknesses of approximately 150–300 μm .

Two conclusions stated in our previous work [16,17] are that preheat layers broaden as the turbulence level u'/S_L is increased above 20 and the turbulent burning velocity curves (seen in Fig. 1b) display non-linear bending for u'/S_L above 20. These two observations provide experimental proof that Damköhler's predictions were correct. He hypothesized that sufficiently large turbulence levels would increase the turbulent diffusivity and lead to broadened preheat layers. He also predicted that since the laminar burning velocity is proportional to the square root of molecular diffusivity, the turbulent burning velocity should be proportional to

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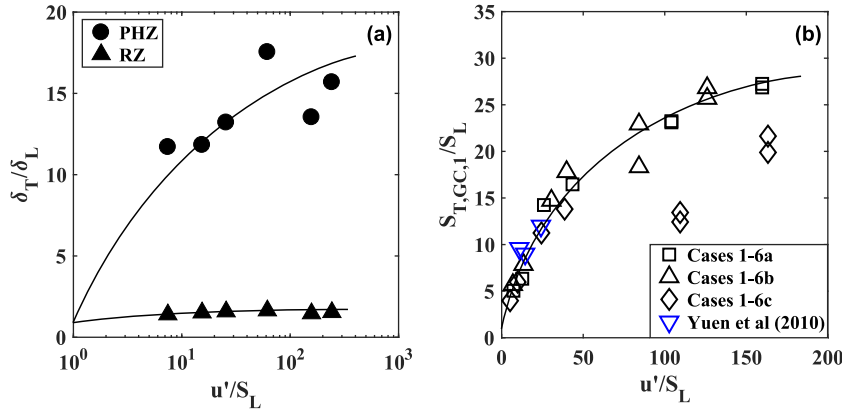


Fig. 1. (a) Average preheat zone and reaction zone thicknesses normalized by the laminar zone thickness as a function of u'/S_L from Ref. [16] and (b) turbulent burning velocity ($S_{T,GC}$, the global consumption speed) normalized by the laminar value as a function of turbulence intensity, from Ref. [17].

the square root of turbulent diffusivity, and would be one source of the bending effect. Our measurements [17] were fitted to the following relations, for u'/S_L up to 243:

$$\frac{S_{T,GC}}{S_L} = \sqrt{1 + c_1 \left(\frac{u'}{S_L} \right)^2} \left(\frac{c_2}{c_2 + \left(\frac{u'}{S_L} \right)} \right) \cdot \left(1 + c_3 \sqrt{\left(\frac{u'}{S_L} \right) \left(\frac{L_x}{\delta_{PHZ,L}} \right) \left(\frac{L_r}{\delta_{PHZ,L}} \right) \left(\frac{\delta_{PHZ,T}}{\delta_{PHZ,L}} - 1 \right)} \right) \quad (1)$$

where $S_{T,GC}$ is the global consumption speed defined by a contour of the mean progress variable of OH, and the preheat zone broadening factor is:

$$\frac{\delta_{PHZ,T}}{\delta_{PHZ,L}} = 1 + c_4 \left(\frac{u'}{S_L} \right)^n \cdot \left(\frac{L_x}{\delta_{PHZ,L}} \right)^m \quad (2)$$

In Eqs. (1) and (2), the variables c_1 , c_2 , c_3 , n , and m are empirical constants that were reported in [17].

However, several unanswered questions remain. We also observed [16,17] that even when u'/S_L was increased to 243, the reaction layers did not broaden appreciably and there were almost no broken reaction layers. Rather, reaction layers were seen to remain thin and continuous. At the conditions of Ref. [17] the computed Kolmogorov scale is much smaller than the reaction layer thickness, so previous predictions that reaction layers will be broken are not in agreement with the measurements. One possible explanation is that the reaction layers are not experiencing the same turbulence level (u') or integral scale that exists at the burner exit. It has previously been suspected that a broadened flame does modify the turbulence in some way [27]. One question is whether or not u' decays in the burner core region, between the burner exit and the upstream boundary of the flame brush. This question was answered by particle image velocimetry (PIV) diagnostics (described below) that show there is no significant variation of u' within the burner core. Most of the paper addresses the second question: whether or not u' decays within the broadened preheat zone, such that only a small fraction of the turbulence reaches the reaction layer. Two hypotheses are assessed. They are: (a) turbulence level (u') decays within the broadened preheat layer, which could be due to viscous effects and/or gas expansion and (b) turbulence level (u') does not decay within the broadened preheat layer, but the integral scale increases in the broad preheat layer. To assess these two hypotheses, conditioned velocities were measured.

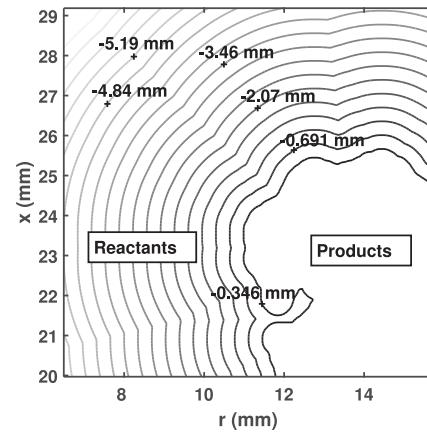


Fig. 2. Example of contours of local distance from the reaction zone. Contours show increasing distance from the instantaneous reaction zone.

1.2. Definition of conditioned velocity

Conditioned velocities in the present study are conditioned on η , which is defined to be the distance from the reaction layer boundary. Therefore, η is equal to 0 at the reaction layer, with positive values of η occurring in the products region and negative η in the reactants. The reaction layer is idealized to be an infinitely thin sheet, which was shown by the flame structure measurements of [16] to be a reasonable approximation. For every pixel in each recorded image, the value of η is determined. An ensemble is created of velocities associated with a certain value of η (plus or minus $\Delta\eta$) and the average of this ensemble is computed. The value of u' where η is negative therefore represents the conditional turbulence level in the reactants, and profiles of similarly conditioned turbulence quantities can be obtained throughout the mean flame brush.

Figure 2 displays some contours of the distance from the upstream boundary of the reaction zone. These contours are obtained from planar laser-induced fluorescence (PLIF) diagnostics that will be discussed in Section 2.2. The products are contained in the lower right-hand corner, and contours show increasing distance into the reactants from the reaction zone boundary. The local value of η is determined by evaluating the nearest distance to a reaction zone edge at each point in the measurement domain. Using this method the local distance can be accurately obtained even in the case of pockets or reaction zone merging, an example of which is shown near the bottom of Fig. 2.

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