A New Measured Regime Diagram of Turbulent Premixed Combustion, Based on Images of Flame Structure

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ABSTRACT

It is proposed to replace the predicted Borghi regime diagram for turbulent premixed flames with a new Measured Regime Diagram that better fits the present measurements and those from previous studies. Thicknesses of preheat and reaction layers were measured along with the probabilities of broken and distributed reactions for 27 cases using CH, OH and formaldehyde laser imaging diagnostics. A new Michigan Hi-Pilot burner provides extreme turbulence levels (u'/S_L) up to 243 and integral scales up to 43 mm, which are 10 times that of previous studies.

Two boundaries on the predicted Borghi diagram do not agree with the measurements: the boundaries of broadened preheat layers (BP) and broken reactions (BR). Instead, we propose a new BP boundary that shows good agreement with the measurements. It is explained by replacing the idea that Kolmogorov eddies must fit inside the flame with the idea that broadening occurs when the turbulent diffusivity exceeds molecular diffusivity. One implication for flamelet modeling is that the measured BP-TR regime (of Broadened Preheat, Thin Reaction layers) extends over a much larger range than is predicted by the Borghi diagram. Broken reactions, which define the upper boundary of the BP-TR regime, were not observed even for turbulence levels u'/S_L of 243, which is five times the predicted value. Thus flamelet models are valid even for extreme levels of turbulence. The preheat layer was broadened by a factor of 14 while, in contrast, the reaction layer was essentially not broadened. For several special cases of stratified flames, both broken and partially-distributed reactions were observed, which is unlike the non-stratified flame. To achieve stratified flames, pockets of cool air were allowed to be entrained into the hot products by reducing the outer co-flow; these cool pockets created broken reactions.

Introduction This work addresses the need to replace the predicted Borghi regime diagram of turbulent premixed combustion with a measured regime diagram (MRD). The measured regime diagram is based on high resolution PLIF imaging of flame structure and it is shown to have regime boundaries that are different from the theoretical Borghi diagram. The motivation for the work is that a regime diagram is a useful indicator of when combustion transitions from thin flamelets to broadened flamelets and then to broken flamelets as the turbulence intensity (u'/S_L) is increased, as explained by Borghi [1], Williams [2] and Peters [3]. A regime diagram also may indicate when (or if) distributed reactions occur. Measured regime boundaries are needed to understand when thin flamelet models [4] are appropriate and when they should be replaced by models that can simulate broadened flamelets, broken flamelets or distributed reactions.

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Unfortunately, many researchers incorrectly have assumed that the predicted Borghi diagram is valid, when in fact it never has been experimentally verified. The Borghi predicted boundaries do not agree with the available measurements. Data of Gulder, Dinkelacker [5, 6] demonstrate that thin flamelets exist even for turbulence levels that are much larger than is predicted by the theoretical Borghi diagram. New laser diagnostics now make it possible to determine a measured regime diagram by imaging the thicknesses of preheat layers and reaction layers.

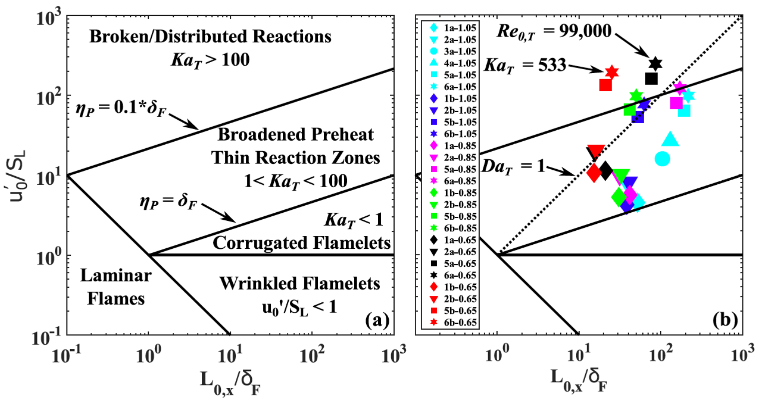

Figure 1. (a, b) Borghi regime diagram in Peters [3]. Two theoretical boundaries are labeled $\eta_P = \delta_F$ (Klimov-Williams thickened preheat layers) and $\eta_P = 0.1\ \delta_F$ (broken reactions).

In previous studies the thicknesses of preheat layers were measured using Rayleigh scattering [5, 6, 7]. In most previous cases the turbulence level (u'/S_L) was less than 24, but in the present work it was increased to 243. The solid and the open symbols in Figs. 1 and 2 indicate when broadening of the preheat zone (by a factor of two) did or did not occur, respectively. The reaction layer thickness is another important quantity of interest; the only two acceptable ways to image reaction layers are CH PLIF and formaldehyde-OH overlap PLIF. In studies of Filatyev et al. [8] and Wabel et al. [9] it was found that the reaction layer thickness is not significantly changed as the turbulence level was increased. Dunn et al. [10, 11] and Zhou et al. [12, 13] did observe broadening of the CH layer near the tip of a jet flame, which could be due the merging of flamelets. No broken reactions were observed in the PLIF studies of Wabel et al. [9] and Filatyev et al. [7]. Some broken layers were seen by Zhou et al. [12, 13] and Dunn et al. [10, 11].

Michigan Hi-Pilot Burner

The Michigan Hi-Pilot Burner in Fig. 2 is described in [9]. It is a piloted Bunsen burner that is designed to achieve very large values of u/S_L, integral scale, and Reynolds numbers, along with a uniform profile of turbulence levels and integral scales across the base of the flame. Reactants issue at mean velocities up to 110 m/s from the central burner that is 21.6 mm in diameter. The large pilot flame consist of a hydrogen-air premixed flame above a 127 mm diameter grid.

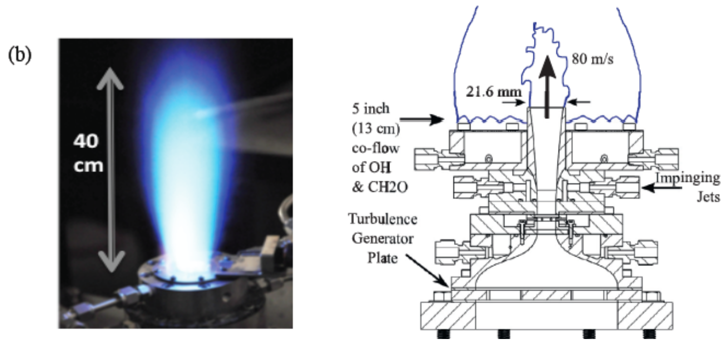

Table 1 Run conditions and parameters for the Hi-Pilot experiment

Case	ϕ	U_0 (m/s)	u' (m/s)	λ_I (mm)	Re_T	Da_T	Ka_T	u'/S_L	$\lambda/\delta_{PH,L}$
2a	1.05	14	2.9	7.5	1,400	25.4	4.7	7.5	31
3a	1.05	32	6.0	20	7,900	33.1	8.5	15	84
4a	1.05	44	10	25	17,000	24.6	16.5	26	105
5a	1.05	64	24	37	58,000	15.1	50.4	62	154
6a	0.65	78	37	41	99,000	1.7	503	243	83

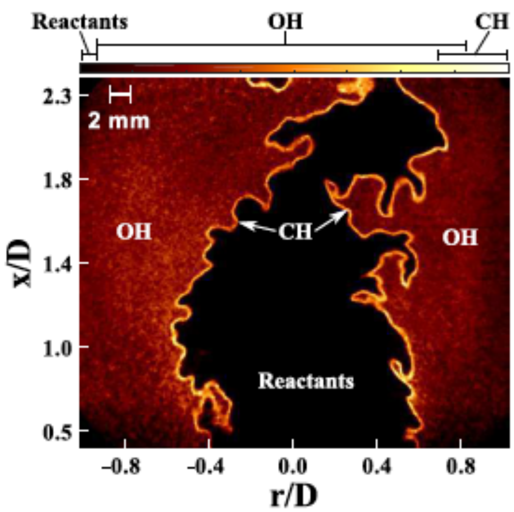

Figure 2. Michigan Hi-Pilot Burner and CH and OH regions for Case 2A.

Preheat zones - thickness and structure for intense turbulence (u'/S_L) up to 243

Fig. 3 shows the instantaneous preheat zones in the Hi-pilot burner. The preheat zone is defined to start where the formaldehyde PLIF signal is 35% of its maximum value and it ends at the reaction zone, where the product of formaldehyde and OH PLIF signals is 50% of its maximum value.

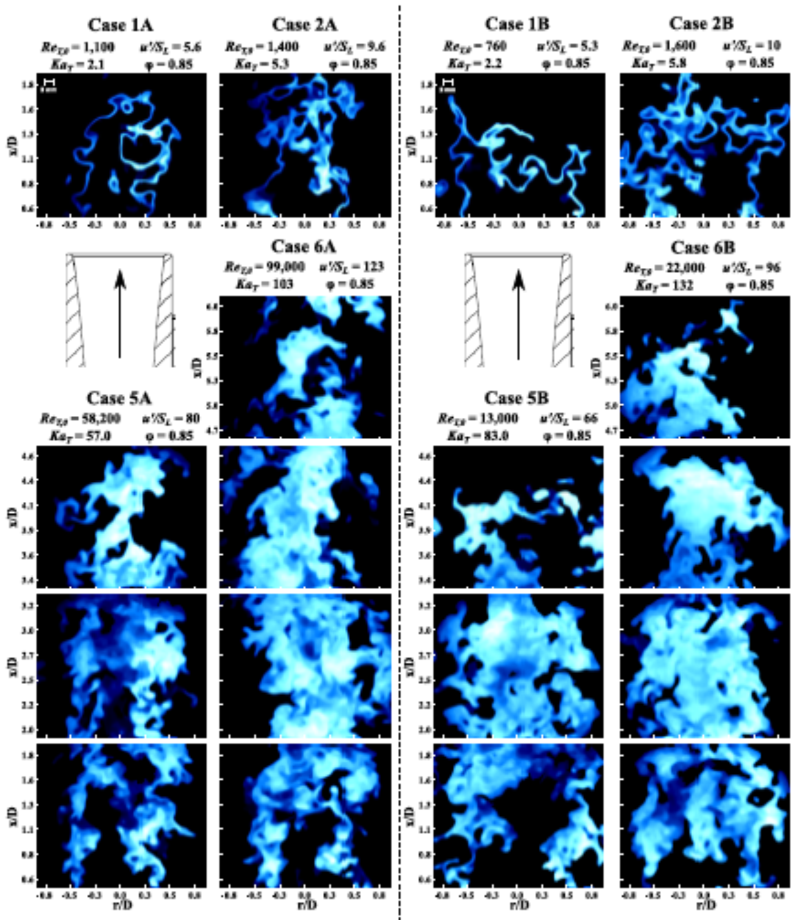

Figure 3. Preheat zone instantaneous images for Re_T from 1,100 to 22,000. Formaldehyde PLIF images are shown. Preheat zone becomes 14 times thicker than the laminar preheat thickness.

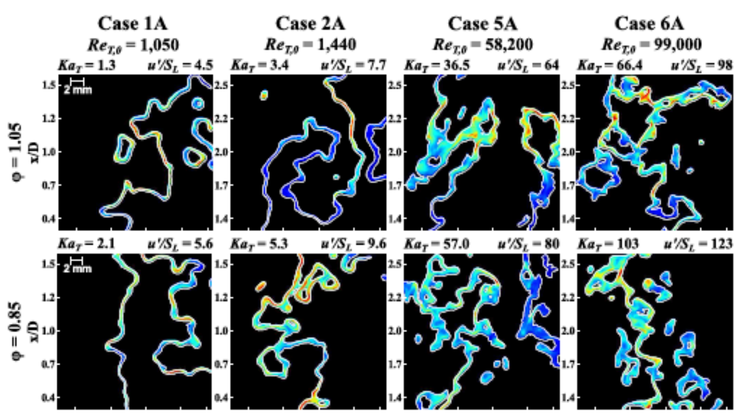

Figure 4. Reaction layers from the overlap method, for u'/S_L from 4.5 up to 123.

The New Measured Regime Diagram (MRD)

Two previously predicted boundaries on the Borghi diagram (Fig. 1) do not agree with measurements that are shown in Fig. 5. Closed symbols on the right represent measured broadened flamelets (BF), while open symbols on the left are measured thin flamelets [4-6].

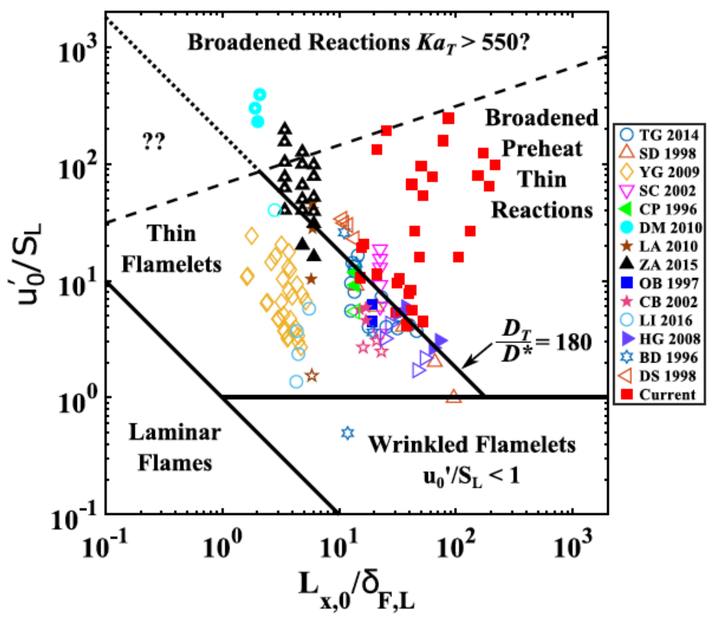

Figure 5. The new Measured Regime Diagram. Closed symbols on the right are measured broadened flamelets. Open symbols on the left are measured thin flamelets.

The measured boundary between broadened and thin flamelets is predicted by the Borghi diagram (Fig. 1) to be a line with positive slope of 1/3. However the measured boundary is the solid line in the center of Fig. 5 that has a negative slope; its slope is -1. An explanation for the new boundary is that preheat zone broadening begins when turbulent diffusivity (D_T) sufficiently exceeds molecular diffusivity (D). The Taylor scale η_T is defined as $L_x\,(u'\,L_x/\nu)^{-1/2}$ and D_T is set equal to $(u'_T\ \eta_T)$ where u'_T is $u'\,[\eta_T / L_x]^{1/3}$. The new criterial $D_T = c_1 D$ leads to the new boundary shown in the middle of Fig. 5 that has a slope of -1.

Conclusions

1. Two predicted regime boundaries on the Borghi diagram for premixed flames were found to disagree with the present measurements. For 27 cases of extremely turbulent flames (u'/S_L up to 243) the preheat layer thicknesses and fraction of broken flamelets were measured.
2. A new Measured Regime Diagram (MRD) is presented in Fig. 5 that has regime boundaries that are a good fit to both the present data and to data reported in previous studies. The measured slope of the BP-TR (broadened preheat-thin reaction layer) boundary is -1, whereas the predicted slope was 1/3. The measured slope of -1 is explained by the broadening of the preheat layer requires that the turbulent diffusivity exceed the molecular diffusivity.
3. For the 27 cases, care was taken to avoid stratification of the product gases. The diameter of the co-flow of hot products was made sufficiently large to prevent any pockets of cold ambient air from

reaching the downstream side of the flame. Thus all 29 cases are "non-stratified" and there were no broken reaction layers observed, even though the turbulence level was five times larger than that of the predicted broken regime boundary.

4. Therefore it is concluded that continuous flamelets exist over a much larger range (at least five times larger turbulence level) than the range suggested by the predicted broken regime boundary on the Borghi diagram.
5. Distributed reactions were not observed for any the 27 non-stratified flames, including cases of Damkohler number that is less than unity. Thus the prediction that the distributed reaction boundary occurs where Damkohler number is unity is not consistent with the measurements.
6. In addition to the 27 cases of "non-stratified" flames, five other cases were studied which were forced to be stratified. The hot co-flow was reduced, forcing pockets of cool air to mix into the products. For these five stratified cases, broken and partially-distributed reactions were observed. Nearly every break in the reaction layer was associated with a nearby pocket of cool entrained air on the product side. Thus the BR (broken reaction) boundary depends on the degree of stratification (DOS) of the products.

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