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Premixed flames subjected to extreme levels of turbulence part I: Flame structure and a new measured regime diagram

Aaron W. Skiba^{a,*}, Timothy M. Wabel^a, Campbell D. Carter^b, Stephen D. Hammack^b, Jacob E. Temme^c, James F. Driscoll^a

^a Department of Aerospace Engineering, University of Michigan, 1320 Beal Ave., Ann Arbor, MI 48109, USA

^b Air Force Research Laboratory, Wright-Patterson AFB, OH 45433, USA

^c U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005, USA

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ABSTRACT

This paper presents high-fidelity flame structure measurements of premixed methane–air Bunsen flames subjected to extreme levels of turbulence. Specifically, 28 cases were studied with longitudinal integral length scales (L_x) as large as 43 mm, turbulence levels (u'/S_L) as high as 246, and turbulent Reynolds ($Re_{T,0}$) and Karlovitz (Ka_T) numbers up to 99,000 and 533, respectively. Two techniques were employed to measure the preheat and reaction layer thicknesses of these flames. One consisted of planar laser-induced fluorescence (PLIF) imaging of CH radicals, while the other involved taking the product of simultaneously acquired PLIF images of formaldehyde (CH_2O) and hydroxyl (OH) to produce “overlap-layers.” The average preheat layer thicknesses are found to increase with increasing u'/S_L and with axial distance from the burner (x/D). In contrast, average reaction layer (i.e. CH- and overlap-layer) thicknesses did not increase appreciably even as u'/S_L increased by a factor of ~ 60 . Furthermore, the reaction layer thicknesses (based on the CH images only) did not increase with increasing x/D . The reaction layers are also observed to remain continuous; that is, local extinction events are rarely observed. Although based on a sequence of combined CH–OH PLIF images acquired at a rate of 10 kHz, it is apparent that when instances of local extinction do occur they are the result of cool gas entrainment. The results presented here, as well as those from 12 prior experimental and 9 numerical investigations, do not agree with the predicted Klimov–Williams boundary on the theoretical Borghi Diagram. Thus, a new *Measured Regime Diagram* is proposed wherein the Klimov–Williams criterion is replaced by a metric that relates the turbulent diffusivity ($D_T = u' L_x$) to the molecular diffusivity within the preheat layer ($D^* = S_L \delta_{F,L}$). Justification for this replacement is based on physical reasoning and the fact that the line defined by $D_T/D^* \approx 180$ accurately separates cases with thin flamelets from those with broadened preheat yet thin reaction layers (i.e. BP-TR flames). Additionally, the results suggest that the BP-TR regime extends well beyond what was previously theorized since neither broken nor broadened reaction layers were observed under conditions with Karlovitz numbers as high as 533, which is five times higher than the theoretical boundary.

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1. Introduction

Characterizing the structure of turbulent premixed flames, based on a condensed set of governing parameters (e.g. turbulence level and integral scale), has been a primary goal of combustion science for the past four decades. The allure of such a simple classification is that it would allow easy identification of the most appropriate formulation for modeling the reaction processes within a given combustion system. Ultimately, this would facilitate the de-

sign and development of efficient, low-emission engines. For example, if the spatiotemporal scales of the primary combustion reactions in a particular system mimic those of a laminar flame, then it is likely that a flamelet model [3] would most accurately simulate the combustion physics associated with that system. However, if a problem possesses locally extinguished and/or significantly broadened reactions, accurately simulating that problem necessitates the use of models equipped to handle such phenomena.

Alas, the general structure of reaction layers within a combustion device is not known a priori. Nonetheless, theoretical attempts (guided by some empirical evidence) have been made to classify turbulent premixed flames into various regimes of combustion [1,3–9]. The central theory used to delimit one regime

* Corresponding author.

E-mail address: skiba@umich.edu (A.W. Skiba).

Nomenclature

$\delta_{CH,L}$	Measured laminar CH layer thickness
$\delta_{F,L,P}$	Laminar flame thickness defined by Peters [1] (see Eq. (1))
$\delta_{F,L}$	Generic laminar flame thickness
$\delta_{OL,L}$	Measured laminar overlap layer thickness
$\delta_{PH,L}$	Measured laminar preheat layer thickness
δ_{RL}	Characteristic reaction layer thickness
$\delta_{RZ,L,P}$	Laminar reaction layer thickness defined by Peters [1]
$\delta_{th,L}$	Laminar thermal thickness
ℓ	Length scale of an arbitrary eddy
ϵ	Turbulent kinetic energy dissipation rate
η	Generic Kolmogorov length scale
η^*	Kolmogorov length scale based on ν^*
η_0	Kolmogorov length scale based on ν_0
λ	Thermal conductivity
ν	Generic kinematic viscosity
ν^*	Kinematic viscosity near the reaction layer
ν_0	Kinematic viscosity of the reactants
ϕ	Equivalence ratio
ρ	Density
c_p	Heat capacity
D^*	Characteristic diffusivity based on Peters definition [1,2] (see Eq. (1))
D_T	Turbulent diffusivity defined as $u' L$
$Da_{T,P}$	Turbulent Damköhler number based on Peters definition [1]
$Ka_{T,P}$	Turbulent Karlovitz number based on Peters definition [1] (see Eq. (4))
L	Generic integral length scale
L_x	Longitudinal integral length scale
$Re_{T,0}$	Turbulent Reynolds number based on the integral length scale and the kinematic viscosity of the reactants
$Re_{T,P}$	Turbulent Reynolds number based on Peters definition [1] (see Eq. (2))
S_L	Unstretched laminar flame speed
u'	r.m.s. of the velocity fluctuations on centerline and 5 mm above the burner
u'_ℓ	r.m.s. of the velocity fluctuations at an arbitrary length scale ℓ

from another rests on dimensional reasoning and scaling principles first introduced by Damköhler. Namely, he theorized that if eddies smaller than the width of a laminar flame exist within a reacting flow, they will penetrate the flame, and through enhanced diffusion, will distort its structure and disrupt its propagation rate. Yet, if all of the eddies within a turbulent flow are larger than the laminar flame thickness ($\delta_{F,L}$), their effect is simply to wrinkle and stretch the flame front without distorting its thickness or time scales. This latter hypothesis forms the basis for the *flamelet* concept [3], which assumes that the turbulent flame front can be treated as an infinitely thin sheet that separates products from reactants and, on a local level, propagates at the laminar flame speed (S_L).

Knowing the range over which the flamelet concept is valid (i.e. when it is appropriate to apply flamelet models) is a practical concern. To address it, Klimov [4] and Williams [7] refined Damköhler's ideas and proposed that when the Kolmogorov length scale (η) becomes smaller than $\delta_{F,L}$, the flame broadens and no longer resembles nor behaves like a laminar flame. Thus, the theoretical boundary between flamelet and non-flamelet regimes is often re-

ferred to as the Klimov–Williams criterion and was initially defined by $\eta = \delta_{F,L}$. In addition to this theoretical limit, several others were consolidated into phase diagrams by multiple authors in the early to mid 1980s (see Refs. [3,5,6,8] and references therein). Each of these diagrams, as well as those presented in Refs. [1,2,8,9], were constructed slightly differently; however, the version most commonly referred to today was first introduced by Borghi [6] and has since been refined by Peters [1–3]. A modified version of the *Borghi Diagram* presented by Peters in Ref. [1], is displayed in Fig. 1a.

As Fig. 1a shows, Peters, and thus Borghi, constructed this diagram with the ordinate and abscissa being represented by the nondimensional turbulence intensity (u'/S_L , where u' is the root-mean-square of the velocity fluctuations) and the ratio of integral length scale (L) to $\delta_{F,L}$, respectively. Note that in this study, and in many prior studies, the longitudinal integral length scale (L_x) is used to place cases on the Borghi Diagram. This is why L_x is used in Fig. 1b, which marks the locations of prior cases as well as those considered here. Furthermore, in order to be consistent with Peters' version of the Borghi Diagram, we have chosen to adopt his definition for $\delta_{F,L}$, namely:

$$\delta_{F,L,P} = \frac{(\lambda/c_p)_R}{(\rho S_L)_0} = \frac{D^*}{S_L}, \quad (1)$$

where ρ is the density, λ and c_p are the thermal conductivity and specific heat capacity, respectively, D^* is a characteristic diffusivity, and the subscripts “0” and “R” indicate whether the parameters were evaluated at a reactant or a reaction layer temperature, respectively. By assuming a reaction layer temperature of 1500 K and employing an empirically based formulation to compute λ/c_p [10], Peters determined that $D^* \approx 7.2 \times 10^{-5} \text{ m}^2/\text{s}$. Then by considering a stoichiometric methane–air flame with $S_L \approx 40 \text{ cm/s}$, he determined that $\delta_{F,L,P} \approx 0.18 \text{ mm}$ [2]. Peters considered this to be an approximate measure of the laminar preheat layer thickness ($\delta_{PH,L}$), which, based on D^* and a fuel depletion rate, he determined was roughly an order of magnitude larger than the laminar reaction layer thickness ($\delta_{RZ,L,P}$) [1].

The limits of the various regimes in Fig. 1a, as well as those in other regime diagrams [1–3,5,8,9], are typically marked by three specific nondimensional parameters: the turbulent Reynolds (Re_T), Damköhler (Da_T), and Karlovitz numbers (Ka_T). Peters [1,2] provided the following definitions for these parameters:

$$Re_{T,P} = \frac{u' L}{S_L \delta_{F,L,P}}, \quad (2)$$

$$Da_{T,P} = \frac{S_L L}{u' \delta_{F,L,P}}, \quad (3)$$

$$Ka_{T,P} = \frac{\tau_{F,L,P}}{\tau_{\eta^*}} = \left(\frac{\delta_{F,L,P}}{\eta^*} \right)^2 = \left(\frac{u'}{S_L} \right)^{\frac{3}{2}} \left(\frac{\delta_{F,L,P}}{L} \right)^{\frac{1}{2}}, \quad (4)$$

where the subscript “P” signifies a variable based on Peters' definitions, $\tau_{F,L,P} = \delta_{F,L,P}/S_L$ is a characteristic flame time scale, and τ_{η^*} and η^* represent the Kolmogorov time and length scales based on a reaction layer temperature (e.g. 1500 K), respectively. Note, however, that in this study, and in most prior studies, the turbulent Reynolds number that is reported is based on the following definition:

$$Re_{T,0} = \frac{u' L_x}{\nu_0}. \quad (5)$$

where ν_0 represents the kinematic viscosity of the reactants. To arrive at the specific definitions in Eqs. (2)–(4), Peters invoked two specific assumptions. The first was that $\delta_{F,L}$ should be defined as in Eq. (1) and the second was that the relevant Kolmogorov scale should be based on a kinematic viscosity evaluated at a temperature associated with the reaction layer (ν^*). Specifically, Peters

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