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Thin reaction zone and distributed reaction zone regimes in turbulent premixed methane/air flames: Scalar distributions and correlations

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ABSTRACT

A series of premixed turbulent methane/air jet flames in the thin reaction zone (TRZ) and distributed reaction zone (DRZ) regimes were studied using simultaneous three-scalar high-resolution imaging measurements, including HCO/OH/CH_2O, CH/OH/CH_2O, T/OH/CH_2O and T/CH/OH/. These scalar fields offer a possibility of revisiting the structures of turbulent premixed flames in different combustion regimes. In particular, CH_2O provides a measure of the preheat zone, CH/HCO a measure of the inner layer of the reaction zone, and OH a measure of the oxidation zone. Scalar correlations are analyzed on both single-shot and statistical basis, and resolvable correlated structures of ~100 μm between scalars are captured. With increasing turbulence intensity, it is shown that the preheat zone and the inner layer of the reaction zone become gradually broadened/distributed, and the correlation between HCO and $[OH]_{LIF}\times[CH_2O]_{LIF}$ decreases. A transition from the TRZ regime to the DRZ regime is found around Karlovitz number of 70–100. The physical and chemical effects on the broadening of the flame are investigated. In the TRZ regime the inner layer marker CH and HCO remains thin in general although occasional local broadening of CH/HCO could be observed. Furthermore, there is a significant probability of finding CH and HCO at rather low temperatures even in the TRZ regime. In the DRZ regime, the broadening of CH and HCO are shown to be mainly a result of local reactions facilitated by rapid turbulent transport of radicals and intermediate reactants in the upstream of the reaction paths. Differential diffusion is expected to have an important effect in the DRZ regime, as H radicals seemingly play a more important role than OH radicals.

1. Introduction

Being motivated by both industrial applications and fundamental scientific enquiries, studies of premixed turbulent combustion have attracted an increasing attention in the past decades. Of paramount importance among these studies is the work towards understanding the interaction between turbulence and flame, which is classified by a variety of combustion regime diagrams that describe the different modes of turbulent premixed flames [1–5]. According to the regime diagram, a key parameter, the so-called Karlovitz number (Ka), is employed which is defined as the ratio between the chemical reaction time associated with the flame and the smallest time scale of turbulence, i.e., the Kolmogorov time. Under the low-intensity and large-scale turbulence condition, i.e., $Ka < 1$, the length scales of turbulence eddies are larger than the flame thickness; turbulence can winkle the flame while not able to modify the preheat and reaction zone structure. The flame propagates as a thin reacting layer separating the reactants and the products, and segments of the wrinkled flame can be considered as a laminar flamelet [4–6]. Peters extended the flamelet concept to the thin reaction zone (TRZ) regime [4] in which the smallest turbulence scale (the Kolmogorov scale) becomes comparable to the flame thickness while still larger than the inner layer thickness of the reaction zone. Peters [4] argued that the flamelet concept remains valid in the TRZ regime, in which the inner layer of the reaction zone stays thin and intact, although the preheat zone can be broadened by the small eddies of comparable sizes to that of the preheat zone. Peters' TRZ regime is supported by a large body of numerical and experimental studies [7–13], while it has also been shown that turbulent burning velocity may not correlate with the flame surface area for flames in the TRZ regime [14,15].

An essentially different scenario can possibly be encountered in a so-called distributed reaction zone (DRZ) regime or broken reaction zone regime in which the Karlovitz number is high (typically $Ka > 100$ [4]). In this regime, it is hypothesized that the Kolmogorov scale can become smaller than the inner layer of the

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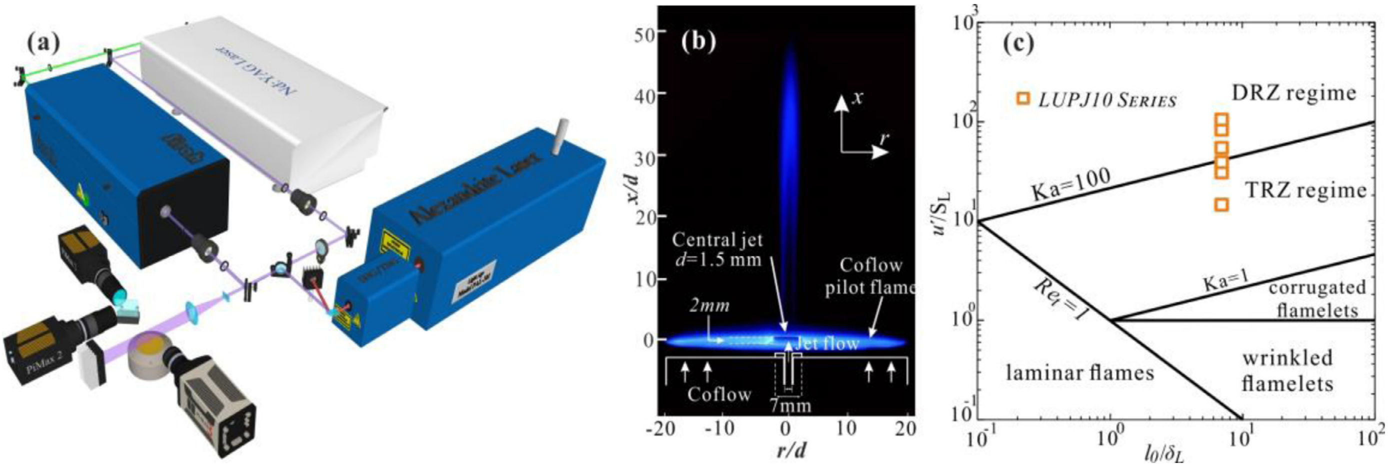

Fig. 1. (a) Experimental setup for simultaneous multi-scalar imaging measurements, and (b) photograph of a LUPJ flame with a schematic plot of the burner employed and (c) conditions of the investigated LUPJ flames in the regime diagram.

reaction zone so that the entire structure of the reaction zone could be substantially distorted by small-eddy penetration. As a possible consequence, the reaction zone could be broadened and/or distributed, resulting in a combustion mode fundamentally distinct from that of a laminar flamelet. However, whether or not this combustion mode (i.e. distributed reactions) can be realized through rapid turbulence mixing has been questioned due to the lack of conclusive experimental evidence of distributed reaction zones or significant reaction zone broadening [16]. Driscoll suggested that a direct experimental evidence of distributed reactions in hydrocarbon flames could be a set of single-shot images that show the CH/HCO layer to be significantly broadened/distributed in space [16]. This is because the CH and HCO radicals are formed through reactions associated with the major heat release in hydrocarbon flames [17,18] and are extremely short-lived, which prohibits them from being transported an appreciable distance from where they are produced. Therefore, a distributed CH/HCO layer is a direct reflection of distributed reactions responsible for CH and HCO production.

It is noted that a number of works have claimed combustion with distributed reactions through various other experimental observations such as vitiated thermal gradients [19,20], absence of flame chemiluminescence [21] or a rapid change of the minimum ignition energy with increasing turbulence intensity [22]. However, these observations alone do not necessarily indicate distributed reactions as the associated reactive species in the reaction zone were not reported.

Recently, we demonstrated that distributed reactions characterized by CH and HCO can be realized in a turbulent methane/air jet flame by varying the jet speed and equivalence ratio [23,24], and in low swirl flames [25] by dilution from ambient air. In this paper we focus on the following two research questions: (1) physical and chemical reasons behind the broadening of the reaction zones; (2) the impact of turbulence-flame interaction on the fields of various key scalars and the correlations among the scalars for flames in the TRZ and DRZ regimes. To reveal the structures of different reaction layers, reactive scalars of OH (oxidation and post-flame zone markers), CH_2O (preheat zone marker [26]), CH and HCO (inner layer reaction zone markers [17]) are selected and measured using planar laser-induced fluorescence (PLIF) together with temperature (T) field using Rayleigh scattering thermometry (RST). Four sets of simultaneous high-resolution three-scalar imaging measurements were performed, which include combinations of HCO/OH/CH_2O, CH/OH/CH_2O, T/OH/CH_2O and T/CH/OH. Instantaneous structures of reactive scalars (i.e. OH, CH_2O, CH and HCO) and temperature (T) are compared together with their derivatives, i.e. two-dimensional (qualitative) OH gradient ($|\nabla[OH]|_{2D}$) and two-dimensional temperature gradient ($|\nabla[T]|_{2D}$) as well as products of OH and CH_2O, of OH and CH, and of OH and HCO, which qualitatively measure the rates of the associated reactions. It has been shown that the HCO concentration is proportional to its production rate that has an excellent spatio-temporal correlation with peak heat release rate (HRR) in laminar methane/air flames [17,27]. However, prior to the recent development of a satisfactory single-shot HCO PLIF technique [28], instantaneous visualization of the HCO radical in turbulent flames was rare. As an alternative approach, the product of OH and CH_2O has been proposed as a qualitative heat release surrogate because it can be related to HCO production through one of the major HCO formation reactions $CH_2O+OH\rightarrow H_2O+HCO$ [29,30]. Although this method has only been experimentally verified in laminar flames, it has been employed widely in many experimental studies of turbulent flames [31–36] owing to the experimental feasibility. To the best of the authors' knowledge, the correlation between HCO and the product of OH and CH_2O in turbulent flames, however, has not been experimentally investigated.

Taking the advantage of multi-scalar imaging in the present work, correlations between different scalars were analyzed on both single-shot and statistical basis. The experimentally resolvable small-scale structures in flames resided in both the TRZ and DRZ regime are identified through the instantaneous correlated structures between scalars. Statistical analyses were performed to investigate correlations of various scalars with temperature in flames.

2. Experimental setup

Figure 1(a) shows the experimental setup employed, which includes a Nd:YAG laser for CH_2O excitation and Rayleigh scattering thermometry at 355 nm, a dye laser for OH excitation at 283.55 nm, and an Alexandrite laser for excitation of CH and HCO at 387.3 nm and 259 nm, respectively. The shot-to-shot fluctuations of all laser energies were about 1%, and the 355-nm laser beam was tuned to *s*-polarization by a half-wave plate to maximize the Rayleigh signal. Further details on the laser-diagnostic system and LIF excitation-detection schemes can be found in [23,28]. Special attention has been paid in the present work to ensure interference-free detection of HCO [28] and CH [37] signals. The CH/HCO LIF emission spectra have been recorded in both laminar and turbulent flame conditions, and no detectable spectral interference signal has been found. Laser beams were spatially combined and focused by

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