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Simultaneous multi-species and temperature visualization of premixed flames in the distributed reaction zone regime

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Abstract

Structures of turbulent premixed flames, operating in the thin and distributed reaction zone regimes, were investigated for stoichiometric premixed methane/air jet flames with jet Reynolds number up to 40,000 and corresponding Karlovitz number up to 286. Multi-species planar laser-induced fluorescence with high spatial resolution was applied to simultaneously image combinations of CH/OH/CH_2O and HCO/OH/CH_2O. In addition, OH/CH_2O imaging was performed in combination with simultaneous Rayleigh scattering thermometry. The CH and HCO layers showed progressive broadening along the axial distance for flames with Reynolds number above 21,000 and the corresponding Karlovitz number above 126. At Reynolds number 40,000 and the corresponding Karlovitz number of 286, a mean CH layer thickness more than 10 times larger than that under laminar condition was observed, providing a clear experimental evidence of distributed reaction zone owing to turbulence/flame interaction. Additionally, spatial correlations between species show that OH and CH_2O locate at mutually exclusive regions. In contrast, both CH and HCO can overlap substantially with CH_2O. The regions of strong CH/HCO signals correspond to regions with weak CH_2O signals. Moreover, CH and HCO are shown to be able to penetrate deeper into the OH layer than CH_2O. Regions where CH and HCO appear distributed show a rather homogeneous temperature distribution with reduced maximum temperature compared with non-distributed conditions.

Keywords: Planar laser-induced fluorescence; Distributed reaction zone; CH and HCO radicals; Turbulent combustion; Premixed methane/air flame

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1. Introduction

Modeling and understanding of high-intensity and small-scale turbulent premixed combustion remain a scientific challenge. Turbulent premixed combustion has been theoretically categorized into regimes depending on the interactions between turbulence and chemistry. For low-intensity and large-scale turbulent flames, the laminar flamelet concept [1] is widely adopted in numerical simulations based on the assumption that the

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smallest scale of turbulence, the Kolmogorov scale, is larger than the length scale of the reaction zones. The flamelet concept has been verified in the wrinkled/corrugated flamelet regimes by many experiments and direct numerical simulations (DNS) [2–4]. Peters [5] described the turbulence/flame interaction in the thin-reaction-zone (TRZ) regime where small eddies are sufficiently small to fit into the preheat zone but still comparatively larger than the reaction zone thickness, thus broadening the preheat zone while the thin reaction zone remains intact. This regime has also been verified in numerical simulations and experiments [6–11].

When the Kolmogorov scale becomes an order of magnitude smaller than the flame thickness (i.e. Karlovitz number, $Ka > 100$), the flame is in the so-called distributed reaction zone (DRZ) regime. In the DRZ regime it is theoretically expected that the smallest eddies can penetrate into the thin reaction zone, and thereby broaden the reaction zone through turbulence-enhanced diffusive transfer of heat and species. In contrast, Poludnenko et al. [12] showed a DNS simulation of methane/air flames, which implies that the flamelet concept could still be valid even in the DRZ regime. However, the single-step chemistry assumed in their simulation could be questionable in the DRZ regime where finite-rate chemistry effects interacting with turbulence are expected to be important. It has also been argued that the DRZ regime may not be realized in practice because the flame front might incline to extinction before being broadened, as evidenced in observations of Meier et al. [13] and Chen et al. [7]. Thus, up to now it seems that no consistent physical understanding of turbulence/chemistry interaction in the DRZ regime has been established, a fact many times leading to the arbitrary assumption that the flamelet concept is always applicable.

It is of particular importance to investigate turbulent combustion in this regime for some practical applications, e.g., stationary gas turbines for power generation [14]. However, numerical and experimental investigations in the DRZ regime are rather limited. Some reported observations of vitiated thermal gradients at highly turbulent conditions might imply the existence of distributed reactions [15]. Nevertheless, a direct measure of radicals such as CH and HCO that only exist in a thin reaction zone, from the flamelet perspective, can be much more convincing. As proposed by Driscoll, “a documented distributed reaction zone is defined as a set of measured images of the heat release region or images of radicals such as CH that are spread out over distances that are many times larger than the thickness of a laminar flame” [16]. To the best of authors’ knowledge, no such persuasive proof that distributed reactions can be generated through turbulence has been reported.

The aim of this work is to gain deepened physical and phenomenological understandings of turbulence/chemistry interaction in the DRZ regime with special emphasis on investigating the feasibility of flame front thickening by turbulence. It has been demonstrated that simultaneous multi-species planar laser-induced fluorescence (PLIF) visualization bears great merits for characterizing turbulent flame structures [17]. Improved PLIF diagnostics of CH [18] and HCO [19] developed recently in our lab provide powerful tools for flame reaction zone characterization. In this work, a series of premixed methane/air flames at conditions with various flow speeds were investigated covering both the TRZ and DRZ regimes. Simultaneous PLIF measurements of CH_2O (typical preheat zone marker) and OH (typical oxidization and post-flame zone marker) were performed synchronously with (a) CH PLIF, (b) HCO PLIF, and (c) Rayleigh scattering temperature measurements in turn.

2. Experimental setup

A hybrid porous-plug/jet burner was employed, consisting of a porous bronze plug (61 mm in diameter) and a central jet. The exit of the central jet is located 2 mm above the porous-plug burner surface, and the outer and inner diameters of the jet are 7 and 1.5 mm, respectively. Figure 1a shows a photograph of a turbulent jet methane/air flame and a schematic of the burner. A laminar methane/air co-flow flame (0.3 m/s, $\Phi = 0.9$) was established on the porous-plug burner, while stoichiometric methane/air jet flames were operated at various flow speeds (v_0) as summarized in Table 1. The flow speeds controlled by mass flow controllers (Bronkhorst) were calibrated at 300 K, giving an uncertainty of 1%. The lean co-flow flame provides a hot environment, sustaining the jet flame through continuous ignition of the fuel/air mixture from the central jet, and preventing the entrainment of ambient cold air into the jet flame. The burner is similar to burners studied in several other groups [7,20,21], where the velocity field was measured at various jet velocities. Based on laminar burning velocity (S_L) data reported in [21], flame structure analysis [22], and Peters formulation of the Karlovitz number (Ka) and turbulent Reynolds number (Re_l) [5], an estimation of the Ka and Re_l has been carried out for the flames studied in this work. The value of Ka is presented in Table 1, which ranges from 10 and 286, covering the TRZ regime (F1, F2) and the DRZ regime (F3–F5). The velocity of turbulent eddies at the integral scale (v') is estimated from the root-mean-square velocity data of Dunn et al. [21] at the height above the burner (HAB) about 30 jet diameters. The integral length (l_0) is estimated as the full width at half maximum of