



Investigation of local flame structures and statistics in partially premixed turbulent jet flames using simultaneous single-shot CH and OH planar laser-induced fluorescence imaging

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Abstract

We report on the application of simultaneous single-shot imaging of CH and OH radicals using planar laser-induced fluorescence (PLIF) to investigate partially premixed turbulent jet flames. Various flames have been stabilized on a coaxial jet flame burner consisting of an outer and an inner tube of diameter 22 and 2.2 mm, respectively. From the outer tube a rich methane/air mixture was supplied at a relatively low flow velocity, while a jet of pure air was introduced from the inner one, resulting in a turbulent jet flame on top of a laminar pilot flame. The turbulence intensity was controlled by varying the inner jet flow speed from 0 up to 120 m/s, corresponding to a maximal Reynolds number of the inner jet airflow of 13,200. The CH/OH PLIF imaging clearly revealed the local structure of the studied flames. In the proximity of the burner, a two-layer reaction zone structure was identified where an inner zone characterized by strong CH signals has a typical structure of rich premixed flames. An outer reaction zone characterized by strong OH signals has a typical structure of a diffusion flame that oxidizes the intermediate fuels formed in the inner rich premixed flame. In the moderate-turbulence flow, the CH layers were very thin closed surfaces in the entire flame, whereas the OH layers were much thicker. In the high-intensity-turbulence flame, the CH layer remained thin until it vanished in the upper part of the flame, showing local extinction and reignition behavior of the flame. The single-shot PLIF images have been utilized to determine the flame surface density (FSD). In low and moderate turbulence intensity cases the FSDs determined from CH and OH agreed with each other, while in the highly turbulent case a locally broken CH layer was observed, leading to a significant difference in the FSD results determined via the OH and CH radicals. Furthermore, the means and the standard deviations of CH and OH radicals were obtained to provide statistical information about the flames that may be used for validation of numerical calculations.

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1. Introduction

Turbulent partially premixed combustion is broadly utilized in practical applications, e.g., in gas turbines for power generation. Due to the expected depletion of fossil fuels as well as the issue of global warming, there is a strong demand to improve the combustion efficiency and to reduce the pollutant emission in modern combustion devices. For this purpose a detailed understanding of the fundamental processes taking place in partially premixed flames is required. It becomes particularly complicated where turbulent combustion is concerned, owing to the complex interactions between the reaction chemistry and the rapid heat and mass transfer. For the analysis of combustion processes, two prominent approaches are commonly applied, numerical simulations based on either physically accurate equations or simplified models, and experimental methods. Often both approaches are employed to complement each other, e.g., when numerical simulations are validated by experimental results [1].

In the field of combustion diagnostics nonintrusive optical methods are of the utmost importance since they provide data from the unaffected system with high temporal and spatial resolution [2]. For instance, the flow field can be visualized by particle image velocimetry (PIV) [3,4]; laser Rayleigh scattering can provide temperature information [5,6]; the laser-induced incandescence (LII) can be used to measure the distribution of nascent soot [7,8]. Another crucial measurement is the concentration and local distribution of chemical species. While spontaneous Raman scattering and coherent anti-Stokes Raman scattering are normally used for the detection of major species [9–16], resonant excitation is required for the detection of minor species such as combustion intermediates. Among the resonant techniques, laser-induced fluorescence (LIF) is one of the most established ones [17,18]. In particular, planar LIF (PLIF) is often used to obtain two-dimensional information such as the spatial distribution of different trace species in flames. In general, quite a few intermediates have been investigated with PLIF in the past. However, in turbulent flames the visualization of one single species usually cannot provide sufficient information. Examples are radicals such as CH and HCO, which exist only in a very narrow region of the reaction zone due to their short lifetimes. From PLIF images showing the spatial distribution of one of these species, the flame propagation cannot be ex-

tracted. In these images it is hard to distinguish between the burnt and unburnt regimes on both sides of the strongly wrinkled thin layer observed. Therefore, a lot of effort has been put into the development of experimental methods enabling simultaneous imaging of two or even more species, or one intermediate and the temperature or velocity field. Ayoola et al. [19] and Pfadler et al. [20] have measured local heat release by simultaneous OH and formaldehyde PLIF in premixed flames. Medwell et al. [21] have visualized the temperature field using laser Rayleigh scattering along with OH and formaldehyde distributions in nonpremixed jet flames. CH PLIF and PIV have been used to investigate local flame structures in nonpremixed flames [22–24]. Petersson and co-workers have characterized a premixed swirl-flame using simultaneous OH/PIV and OH/Rayleigh methods [25,26]. However, there is one combination of radicals that has been chosen more often than others, namely CH and OH.

The CH radical is an interesting species to be utilized as a flame front marker in spite of its low number density [27]. This is because of the fact that it exists only in a very narrow layer of the reaction zone taking part in the decomposition process of the fuel molecules in hydrocarbon flames. Furthermore, it plays a key role in the formation of nitric oxide, which is an important pollutant in combustion [28]. Therefore, various techniques have been developed for the detection of CH, e.g., LIF [29,30], cavity ring-down absorption spectroscopy [29], two-color resonant four-wave mixing [31], degenerate four-wave mixing [32], tunable diode laser absorption [33], and polarization spectroscopy [34]. However, CH PLIF applications have been limited to stoichiometric, rich, or nonpremixed flame conditions in most studies, since the number density of CH is strongly dependent on the local equivalence ratio [35]. Recently Li et al. have shown that the use of a pulsed alexandrite laser enabling multiple rotational line excitation (multiplex) facilitates CH PLIF imaging with a high signal-to-noise ratio [35] over a wide range of stoichiometric ratios. This approach enables single-shot applications in turbulent lean premixed flames. In contrast, the OH radical exists in a much larger flame region, since it is only consumed in three-body collision reactions within the recombination zone [36]. Therefore it is widely utilized as a reaction zone marker in combustion research (see, e.g., Ref. [37] and references therein). A particularly interesting feature of single-shot OH imaging is that it can provide information

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