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Simultaneous formaldehyde PLIF and high-speed schlieren imaging for ignition visualization in high-pressure spray flames

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Abstract

We applied simultaneous schlieren and formaldehyde (CH_2O) planar laser-induced fluorescence (PLIF) imaging to investigate the low- and high-temperature auto-ignition events in a high-pressure (60 bar) spray of n-dodecane. High-speed (150 kHz) schlieren imaging allowed visualization of the temporal progression of the fuel vapor penetration as well as the low- and high-temperature ignition events, while formaldehyde fluorescence was induced by a pulsed (7-ns), 355-nm planar laser sheet at a select time during the same injection. Fluorescence from polycyclic aromatic hydrocarbons (PAH) was also observed and was distinguished from formaldehyde PLIF both temporally and spatially. A characteristic feature previously recorded in schlieren images of similar flames, in which refractive index gradients significantly diminish, has been confirmed to be coincident with large formaldehyde fluorescence signal during low-temperature ignition. Low-temperature reactions initiate near the radial periphery of the spray on the injector side of the spray head. Formaldehyde persists on the injector side of the lift-off length and forms rapidly near the injector following the end of injection. The consumption of formaldehyde coincides with the position and timing of high-temperature ignition and low-density zones that are clearly evident in the schlieren imaging. After the end of injection, the formaldehyde that formed on the injector side of the lift-off length is consumed as a high-temperature ignition front propagates back toward the injector tip.

Keywords: Spray combustion; Diesel combustion; High-speed imaging; Formaldehyde PLIF; Schlieren imaging

1. Introduction

Ignition characteristics and flame stabilization represent two of the critical factors considered in the design and operation of compression ignition engines as they determine operating limits and influence pollutant formation. As such, it is imperative that combustion models accurately reproduce experimental ignition delay time and lift-off length measurements. Modeling efforts from various research institutions, however, show inconsistency between experimentally determined and modeled ignition delay times and lift-off lengths [1–6]. To improve the current understanding of ignition and stabilization processes in high-pres-

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sure spray flames and enable the development of more accurate models, information is needed about the temporal evolution of the spray as it progresses through low- and high-temperature ignition stages and subsequently stabilizes as a lifted diffusion flame.

In compression ignition engines, low-temperature chemical reactions yielding radicals and reactive intermediates precede the high-temperature ignition event and may play an important role in subsequent stabilization of the quasi-steady lifted flame [7,8]. While some of the aforementioned species can be visualized using planar laser-induced fluorescence (PLIF), limitations associated with lasers and/or intensified cameras have constrained most such measurements to a single-shot per injection event. Using an array of lasers to generate a train of pulses and a framing camera, researchers have acquired up to eight sequential time-resolved images of fuel-, formaldehyde-, and OH-PLIF spaced 10 μs apart during a single engine cycle [9,10]. Recent developments in high-speed burst lasers and high-speed intensified cameras have also permitted PLIF imaging measurements at rates as high as 12 kHz with a single laser and camera setup [11]. Such instrumentation can be cost-prohibitive, however, and has not yet been widely used throughout the engines and spray combustion communities. Moreover, even at 12 kHz critical events during the ignition process can be missed. In the present work, we apply simultaneous high-speed schlieren imaging at 150 kHz and single-shot formaldehyde PLIF at various timings as a simpler alternative to high-speed PLIF for visualizing the temporal evolution of a reacting spray.

Several research groups have used high-speed schlieren imaging to visualize low-temperature ignition processes in diesel sprays [12–15]. In those experiments, the low-temperature ignition event was observed as a local "softening" of refractive index gradients near the spray head. This phenomenon was attributed to the consumption of fuel vapor resulting in the production of intermediate species and heat release that increased the local temperature to a value closer to that of the ambient gases. Consequently, the local refractive index value approached that of the surrounding gases rendering the schlieren effect less pronounced. As formaldehyde (CH_2O) has been observed by PLIF imaging during the low-temperature ignition event, it was supposed that the softening of refractive index gradients in the schlieren imaging would be coincident with regions of formaldehyde and that the formaldehyde would be consumed following high-temperature ignition. The present study investigates this hypothesis by performing high-speed schlieren with simultaneous single-shot formaldehyde PLIF from the same perspective.

2. Experimental setup

2.1. Constant volume pre-burn combustion vessel

Sprays of n-dodecane ($C_{12}H_{26}$) were injected into a pre-burn combustion vessel that simulates the thermodynamic conditions of modern compression-ignition engines [15,16]. A common-rail single-hole diesel fuel injector (#210370, 90-μm orifice) belonging to the family of Spray A injectors of the Engine Combustion Network (ECN) [15] injected fuel at 1500 bar for approximately 1.5 ms. The injection duration and ambient condition for reacting sprays in this work corresponds to the ECN Spray A target (i.e., 900 K, 22.8 kg/m^3, and 15 vol.% O_2). For the non-reacting cases investigated, the target ambient oxygen concentration was zero.

2.2. Optical diagnostics

A large beam-splitter (Edmund Optics #43-362) enabled simultaneous PLIF and schlieren imaging of the combustion event from the same perspective as shown in Fig. 1. Images captured from the same perspective allow for a direct comparison of flame structures observed from both diagnostics, which are discussed in detail below.

2.2.1. Formaldehyde PLIF imaging

Radiation at 355 nm (100 mJ/pulse), produced by a 10-Hz (7-ns pulse) Quanta-Ray Nd:YAG laser and formed into an 80-mm × 0.3-mm sheet, excited the formaldehyde fluorescence. The laser sheet intersected the fuel jet from the bottom of the vessel and passed through the jet centerline as shown in Fig. 1. A flat field correction for the laser intensity profile along the spray axis, which would result in a more even representation of the fluorescence signal, was not made; however, we do not believe this affects the qualitative comparisons of the PLIF signal at different timings ASOI. An intensified CCD camera (Princeton Instruments, PI-MAX3) with a 250-ns gate time

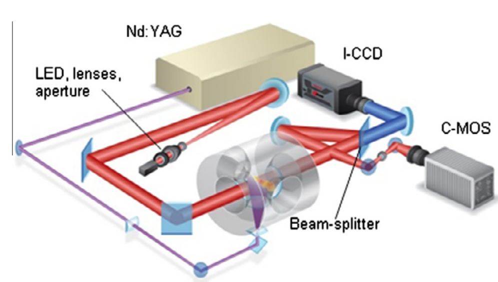

Fig. 1. Schematic diagram of the high pressure combustion vessel and optical arrangement for simultaneous high-speed schlieren imaging and formaldehyde PLIF.

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