Available online at www.sciencedirect.com
ScienceDirect
Proceedings of the Combustion Institute 33 (2011) 767–774
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Development of high-repetition rate CH PLIF imaging in turbulent non-premixed flames

Naibo Jiang, Randy A. Patton, Walter R. Lempert, Jeffrey A. Sutton *

Department of Mechanical Engineering, The Ohio State University, Columbus, OH 43210, USA

Available online 1 September 2010

Abstract

We report on the development of high-repetition rate planar laser-induced fluorescence (PLIF) imaging of the CH radical in turbulent flames. This paper presents what the authors believe to be the first multi-frame, high-speed CH PLIF image sequences captured in a turbulent non-premixed jet-flame. The high-repetition rate CH PLIF measurements were made using a combination of a custom pulse burst laser system operating at a 10-kHz repetition rate, an in-house optical parametric oscillator (OPO) with frequency mixing for 390-nm laser pulse generation, and a high-framing rate ICCD camera for high-speed image capture. The 1064-nm output of the pulse burst laser is frequency-tripled (355 nm) and used to pump the OPO, which can be operated in a narrow bandwidth (300 MHz) or broadband (4 cm^{-1}) mode. The OPO system produces a burst of laser pulses near 615 nm, which can be subsequently mixed with residual 1064-nm output from the pulse burst laser to generate a series of 390-nm pulses separated by less than 100 μs. The tunable ultraviolet output around 390 nm is then used to excite the B–X (0, 0) band allowing high-speed image sequences of the CH radical to be acquired from the B–X(0, 1), A–X(1, 1), and A–X(0, 0) bands near 430 nm. In this paper, we present results using the narrow bandwidth mode of the laser. By injection seeding the OPO with a single-frequency diode laser, we can obtain spectrally-narrow output at 390-nm, which allows imaging of CH with only 0.4 mJ/pulse of laser energy. Ten-kilohertz-CH PLIF image sequences from a turbulent non-premixed flame are reported as an example of the potential of this diagnostic system. Although, the signal-to-noise ratio (SNR) is marginal, we discuss future improvements to the system to increase the SNR to levels comparable to that achieved with traditional low-repetition rate systems.

Keywords: CH PLIF; Pulse burst laser; OPO; Turbulent non-premixed flames; High-speed diagnostics

1. Introduction

The CH radical has long been considered an appropriate marker of the inner reaction zone in both non-premixed and premixed hydrocarbon flames since its location marks the final step in hydrocarbon fuel decomposition (e.g., [1–4]). The narrow spatial profile of the CH radical is well correlated with flame location and heat-release rate (e.g., [2,4]) and its disappearance has been shown to correlate strongly with flame extinction (e.g., [2,3]). Previous turbulent combustion studies have used the CH layer obtained from planar laser-induced fluorescence (PLIF) diagnostics to visualize and investigate turbulence–chemistry interactions including flame wrinkling,

* Corresponding author. Address: Department of Mechanical Engineering, The Ohio State University, 201 W. 19th Ave., Columbus, OH 43210, USA. Fax: +1 614 292 3163.
E-mail address: sutton.235@osu.edu (J.A. Sutton).

1540-7489/$ - see front matter © 2010 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.proci.2010.05.080

flame propagation, flame liftoff and stabilization, and flame response from unsteady fluid mechanics. All of the previous studies have relied on single- or double-pulsed realizations of the CH radical due to the low-repetition rates of commercial laser systems (10 s of Hz). In this aspect, the reaction zone behavior (as identified from the CH layer) is qualified by a series of temporally-uncorrelated instantaneous images.

However, turbulent combustion is non-periodic and is characterized by a time-dependent coupling between turbulent fluid mechanics and finite-rate flame chemistry. Because turbulent combustion processes are highly transient, information is needed that is resolved in *both space and time*. This requirement dictates that the imaging of multi-dimensional scalar fields such is at much faster rates than typical characteristic time-scales of the turbulent processes ($>>$1 kHz). This is especially important for combustion radicals such as CH that serve as markers for the primary reaction zone since processes such as flame extinction and re-ignition are not statistically stationary and cannot be characterized properly by statistically-uncorrelated measurements. In order to monitor the evolution of the reaction zones using CH PLIF diagnostics, multiple images must be recorded sequentially and the time between images must be small enough such that the images are temporally correlated.

Currently, there are few reported studies of high-speed imaging in combustion environments and even these have been limited to diagnostic applications such as particle imaging velocimetry (PIV) and OH PLIF, which require low individual pulse energies. The scarcity of experiments detailing the temporally-evolving nature of turbulent flames has been severely constrained by the lack of available laser technology. As an example, CH PLIF imaging typically is performed by using a high-energy, pulsed laser to pump a dye laser to generate 390 nm directly or to generate tunable visible radiation that may be subsequently converted to the desired UV output via frequency-doubling or sum-frequency mixing. Commercially-available high-energy laser systems including Q-switched Nd:YAG or excimer lasers are limited to pulse repetition rates of 10 to 300 Hz, while commercially-available high-repetition-rate lasers such as Nd:YLF, Nd:YVO_4, and copper vapor lasers are limited to low pulse energies ($<$10 mJ). While high-speed PIV measurements require only modest pulse energies due to high signal levels from the Mie scattering of seeded particles, scalar measurements are much more complicated. Because of the low pulse energies available from commercial high-repetition rate laser systems and the difficulties of pumping conventional dye laser systems at high-repetition rates, only OH PLIF (due to its high concentrations in flames) has been successfully demonstrated for continuous, real-time, multi-dimensional monitoring of a reactive scalar.

Recently, continuous high-speed imaging of the OH radical using a frequency-doubled, Nd:YLF-pumped dye laser operating at 282 nm has been demonstrated (e.g., [5–9]). To date, measurements using these laser systems have been limited to repetition rates less than 10 kHz to avoid photobleaching and triplet-state population of the organic dye. Furthermore, because of a trade-off in repetition rate and pulse energy, the systems typically are operated at lower repetition rates such at 5 kHz to achieve suitable pulse energies ($\sim$100 μJ/pulse) for OH PLIF. As a note, it will be shown later in this paper that this level of pulse energy is much too low for CH PLIF imaging. Paa et al. [10] used a frequency-tripled Yb:YAG at 343 nm to excite "hot bands" of the OH radical at 1 kHz. Even though this experimental system is straightforward (one laser), the transition probability of the (0, 1) transition is 100 times lower than the (1, 0) band at 283 nm, negating the higher achievable pulse energies compared to the frequency-doubled, Nd:YLF-pumped dye laser systems described.

As an alternative to a continuous duty cycle, previous authors have demonstrated the ability to generate a limited number of high-energy pulses at high-repetition rates. Initial work at Lund consisted of "clustering" conventional Nd:YAG-pumped dye laser systems and ICCD camera technology to capture eight sequences of the OH concentration fields via PLIF (e.g., [11–13]) in turbulent non-premixed flames during transient events such as ignition and local flame extinction. Starting with 270 mJ per individual pulse at 532 nm, they were able to generate eight pulses at 282 nm, with average pulse energy of 1 mJ and a minimum inter-pulse period of 125 μs, constrained by the high-intensity pumping requirement of the dye laser. Recently, Sjoholm et al. [14] used the same laser system to pump an optical parametric oscillator (OPO) system instead of a dye laser and frequency-double the output for OH PLIF measurements. Although the OPO system overcomes the inter-pulse spacing limitation imposed by the dye laser, an additional limitation of this "clustered" approach is the number of output pulses available; simply put, increasing the record length of the image sequence requires additional laser sources, which quickly becomes cost prohibitive.

Another well-known approach to making high-speed measurements (over a limited duty cycle) is what has become known as "pulse burst mode". Wu et al. [15] demonstrated the first generation of this type of "pulse burst" by amplifying a low-power continuous wavelength (cw) laser using a conventional flashlamp-pumped amplifier and then forming this one long pulse into a burst of pulses through a pockels cell slicer, followed by additional amplifier stages. Subsequently, Lempert and coworkers [16] and Thurow et al. [17] have developed effective second and third genera-