Combustion and Flame 000 (2018) 1–14

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Dielectric-barrier-discharge plasma-assisted hydrogen diffusion flame. Part 1: Temperature, oxygen, and fuel measurements by one-dimensional fs/ps rotational CARS imaging

Jonathan E. Retter [a,b,*], Gregory S. Elliott [b], Sean P. Kearney [a,c]

[a] Engineering Sciences Center, Sandia National Laboratories, Albuquerque, NM 87185, United States
[b] Department of Aerospace Engineering, The University of Illinois at Urbana-Champaign, 306A Talbot Lab 104 S. Wright St, Urbana, IL 61801, United States
[c] Spectral Energies LLC, 4065 Executive Drive, Dayton, OH 45430, United States

ARTICLE INFO

Article history:
Received 6 October 2017
Revised 16 January 2018
Accepted 17 January 2018
Available online xxx

Keywords:
Laser diagnostics
Femtosecond CARS
Plasma-coupled combustion
Temperature
Fuel
Oxygen

ABSTRACT

One-dimensional hybrid fs/ps CARS imaging provides single-laser-shot measurements of temperature, oxygen, and hydrogen in a plasma-assisted hydrogen diffusion flame. The coaxial dielectric-barrier-discharge burner collapses the *Re* ∼50 hydrogen diffusion flame to within ∼5 mm of the burner surface at an applied AC potential of 8.75 kV at 18 kHz, coinciding nicely with the full spatial extent of the 1D CARS measurements. Translating the burner through the measurement volume allowed for measurements at numerous radial locations in increments of 1 mm with a resolution of 140 µm × 30 µm × 600 µm, sufficient to resolve spatial gradients in this unsteady flame. Longer probe delays, required for improved dynamic range in regions of high temperature fluctuations, proved difficult to model as a result of a nontrivial decay in the O_2 Raman coherence arising from complexities associated with the triplet ground electronic state of the O_2 molecule. Oxygen linewidths were treated empirically using the observed O_2 coherence decay in spectra acquired from the product gases of lean, near-adiabatic H_2/air flames stabilized on a Hencken flat-flame burner. While still leading to errors up to 10% at worst, the empirically determined Raman linewidth factors eliminated any systematic error in the O_2/N_2 measurements with probe delay. Temperature measurements in the Hencken Burner flames proved to be insensitive to probe pulse delay, providing robust thermometry. Demonstration of this technique in both the canonical Hencken burner flames and a new DBD burner validates its effectiveness in producing multiple spatially resolved measurements in combustion environments. Measurements in the DBD burner revealed an unsteady, counterflow flattened flame structure near the fuel orifice which became unsteady as the reaction zone curves towards the surface for larger radial positions. Fluctuations in the fuel concentration were largest at the source, as the large, plasma-generated, unsteady external toroidal vortex that dominates the transport in this flame provides enhanced ventilation of the flame surface in close proximity to the fuel tube.

1. Introduction

Ultrafast CARS schemes are well-documented to have several advantages over more traditional nanosecond CARS for reacting-flow measurements. These ultrashort-pulse approaches deliver high signal strength at flame temperatures via a more efficient preparation of the Raman coherence [1], and the nearly Fourier-transform-limited nature of femtosecond laser pulses delivers a more stable broadband Stokes source than nanosecond dye lasers, resulting in enhanced measurement precision [2–4]. Demonstrations of "hybrid" femtosecond/picosecond CARS schemes are now myriad in the literature [4–17]. Broadband femtosecond pulses prepare a Raman coherence, which is subsequently probed by a frequency-narrow, picosecond pulse to provide high spectral resolution of the resulting CARS signal. Short-pulse CARS approaches have proven robust regardless of the method chosen to generate the frequency-narrow picosecond probe pulse and can reduce or eliminate uncertainties associated with collisional Raman linewidths. Introduction of a short-duration (<10 ps) probe pulse, results in collision-free spectra at short probe delays, essentially eliminating the need for collisional modeling and linewidth data [2,4,13,18–22]. Longer duration (∼60–100 ps) frequency-narrow probe pulses enable resolution of isolated N_2 and O_2 transitions in pure-rotational CARS spectra, allowing one to infer collisional

* Corresponding author at: Department of Aerospace Engineering, The University of Illinois at Urbana-Champaign, 306A Talbot Lab 104 S. Wright St, Urbana, IL 61801, United States.

E-mail address: retter2@illinois.edu (J.E. Retter).

https://doi.org/10.1016/j.combustflame.2018.01.031
0010-2180/Published by Elsevier Inc. on behalf of The Combustion Institute.

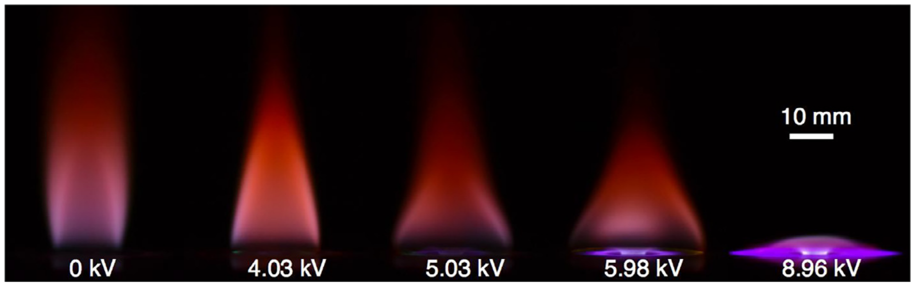

Fig. 1. Flame behavior with increasing peak applied voltage from left to right at 18 kHz.

linewidths by monitoring the decay of the isolated Raman lines in time with a probe-pulse delay scan [8,23–27] or on a single laser shot with multiple time-delayed probe beams [28]. The high signal levels afforded by femtosecond pump/Stokes Raman preparation and high-energy, frequency-narrow probe pulses from picosecond Nd:YAG regenerative amplifiers readily enable extension of fs/ps rotational CARS to 1-D [12,29] and even 2-D [30,31] imaging for spatially-resolved single-laser-shot measurements of temperature, relative oxygen concentrations, and if the bandwidth is available, relative fuel and product concentrations as well [12]. The 1-D line imaging method combines the ability to capture large temperature gradients with high dynamic range in a single image with fine spatial resolution – both requirements for measurements in unsteady and turbulent flames.

For this study, the 1-D hybrid fs/ps CARS technique developed by Bohlin and Kliewer [12,29] is applied to an AC dielectric-barrier-discharge (DBD) hydrogen diffusion-flame burner to resolve the temperature, oxygen concentration, and hydrogen concentration throughout the flame for a certain applied voltage. The use of plasma [32], or simply an electric field [33], to enhance combustion has promise for increased radical production, soot suppression, ability to vary the ignition threshold, and flame shape alteration [34–38]. For the burner in this study, an AC-DBD plasma was incorporated coaxially with the fuel tube to examine the ignition threshold benefits [39] and the alterations in the flow field of a hydrogen diffusion flame [40]. Coupling this new burner with the simultaneous measurements available from the line CARS technique maps out three primary (temperature, fuel, oxidizer) scalar quantities of interest in the flame, providing quantitative data for validation of computational modeling efforts to be presented as a part-2 companion paper to this article [41].

The effect of the DBD plasma on the laminar H_2 diffusion flame is shown in Fig. 1, where time-averaged broadband emission imaging of the flame structure for varying applied voltages at an AC frequency of 18 kHz is shown here, and explained in detail in the companion paper [41]. The orange glow is from a sodium impurity in the quartz burner substrate, whereas the purple at higher applied voltages is emission from the nitrogen second positive system (N_2 $C^3\Pi - B^3\Pi$) associated with the DBD plasma. With increasing voltage, the flame base expands and the flame height decreases, until a threshold voltage is reached, and the flame collapses to a region within ∼5 mm from the quartz surface in which the fuel-tube is embedded. The reference, zero-voltage flame and applied voltages below ∼8 kV produce a laminar flame with a buoyancy-driven flickering frequency that steadily decreases with applied voltage until collapse of the flame structure results in a highly unsteady flow with no dominant frequency content. The 8.75 kV applied voltage used in this study was sufficient to maintain the collapsed shape of the flame, defined visually by the flame furthest to the right in Fig. 1. As explained in [41], the DBD plasma results in a body force that is proportional to the product of the local charge-density gradient and the electric field. This body force induces a toroidal vortex that is positioned inside the flame zone at low applied voltages, and moves radially outward with increased electrical input to widen the flame base, as seen in Fig. 1 for $V = 0$–6 kV. At a critical voltage level near 8–9 kV, the vortex ring and heat release begin to overlap, resulting in an increase in energy coupled to the plasma and a sudden move of the vortex core to a position radially outward from the reaction zone. A schlieren image for the $V = 8.75$ kV flame is shown in Fig. 2, which reveals a dome-like flame structure above the fuel-tube orifice surrounded by the toroidal vortex of hot gas. Temperature and species measurements presented here are limited to the center, dome-like region, near the fuel tube and along the quartz surface, where the highest flame temperatures are expected. A notional depiction of the velocity field in the neighborhood of the fuel tube, based on PIV measurements [41], is shown on the right-hand side of Fig. 2. The flow is dominated by the vortex-ring structure positioned radially outward from the reaction zone, which enhances fluid mixing, brings air and combustion products toward the jet centerline, and creates an unsteady, opposed-flow diffusion-flame structure [41].

2. Experiment

2.1. DBD Burner

The coaxial AC-DBD burner features a 3.8 mm inner-diameter copper fuel tube as the ground electrode, an encapsulated copper ring for the high-voltage electrode, and a quartz dielectric barrier as detailed in Fig. 3, with more details provided elsewhere [40]. The red wire in the electrical schematic of Fig. 4a is the high-voltage lead, generated from the combined system of a Protek B8003FD Function Generator, Crown XTi 4000 Amplifier, and a custom Corona Magnetics INC high-voltage transformer (turn ratio 1:137.5). The high-voltage lead was monitored with a Tektronix P6015A HV probe and a digital oscilloscope. While not recorded for these measurements, the power per AC period is found using the monitor capacitor method [42], accomplished here by recording the voltage across a Kemet Ceramic 470 pF capacitor on the ground side of the circuit with a Tektronix TPP0201 10:1 voltage probe. For this study, the actuator was operated at 18 kHz, with a voltage amplitude of 8.75 kV, and coupled with a hydrogen flowrate of 1 L/min. The Reynolds number based on cold-flow properties of H_2 and using the copper tube electrode diameter (3.8 mm) was ∼50, resulting in a flickering laminar flame in the absence of plasma-assisted conditions. The quartz surface temperature was not explicitly monitored throughout the experiment, although acquisition times were limited to 25 s (500 laser shots at 20 Hz) to allow the surface to cool between runs. From previous measurements of a collapsed flame at 9 kV, over 25 s of run time may result in up to an increase of ∼2 W per AC cycle from start to finish due to an increase in quartz surface temperature of ∼30 K as measured by an IR probe. Based on these earlier measurements, we estimate a burner surface temperature of 570–700 K in our experiments.