Spatially correlated temperature, oxygen, and fuel measurements in a plasma-assisted hydrogen

is paper describes objective technical results and analysis. Any subjective views or opinions that might be expres
the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Governm

where the red wire represents the high voltage lead to the ring electrode

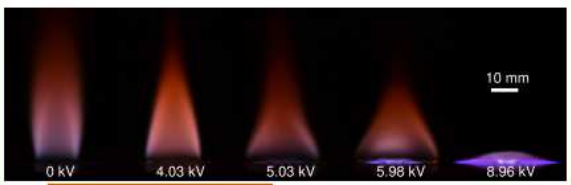
Center for Exascale Simulation of Plasma-Coupled Combustion

SAND2017-7774C

Motivation

XPACC @ UIUC

- Exascale Simulation of Plasma Coupled Combustion
- Predictive simulations need experimental targets/validation
- Hydrogen diffusion flame coupled with a DBD plasma
  - Simple geometry, simple chemistry, with an order of magnitude effect on the flame structure



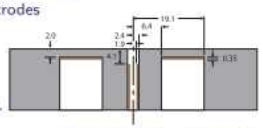
DBD Burner

Dielectric Barrier Discharge Plasma

- Coaxial, AC DBD actuator: copper electrodes, quartz dielectric
  - High temperature tolerance of quartz
  - (Fuel) tube and ring electrodes
  - Self-limiting AC discharge
  - No movable parts

Operating Conditions

- 1 L/min H_2 into quiescent air
- 0-9 kV @ 18 kHz



↑ Burner dimensions in millimeters

Initial Results

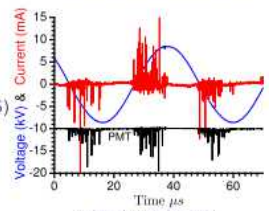
↓ Typical voltage-current curves

Particle Image Velocimetry (PIV)

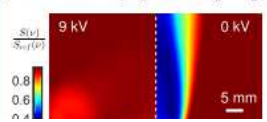
Seeding in the flame was achieved by use of a vaporized silica precursor added to the fuel flow which reacts with oxygen at high temperature to produce silica particles. Results reveal an external toroidal vortex helping to bring air to the reaction zone.

Filtered Rayleigh Scattering (FRS)

FRS images are coupled measurements of species concentrations and temperature for negligible velocity, constant pressure applications. Images are are a plane through the center of the burner, demonstrating the drastic structural differences with applied potential.



↓ Raw Filtered Rayleigh Scattering Images



↓ PIV Image for 9 kV

1D Hybrid CARS Imaging

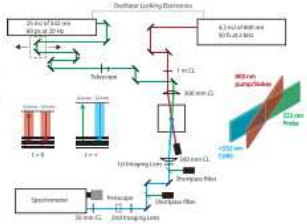
fs pump/Stokes with a ps probe

Experimental Setup

The coupled preparation fs pump/Stokes beam from a fs amplifier was RF locked to a separate ps laser system which produced the time-delayed probe pulse. Both beams were focused horizontally, producing a ~5mm vertical beam crossing line that was dual imaged onto the spectrometer slit. The resulting vertical resolution was ~400μm with a 600μm measurement length.

Time Delayed Probing

Probing the impulsively created Raman coherence eliminates the effects of the nonresonant background while also assisting with dynamic range concerns between cold and hot gas regions. The decay of the hybrid CARS signal is dependent on the linewidths of each rotational states, thus lower states (and lower temperatures) decay faster than higher energy (higher temperature) states. This allows for large temperature gradients to appear in a single image.



↑ Experimental Setup

↓ Raman resonant polarization

Hybrid CARS Model

The model only includes the Raman resonant polarization, as again with time-delayed probing the nonresonant background is deemed negligible. The temporal response of the polarization is convoluted with the probe temporal profile to generate the CARS signal. Experimental spectra are then fit to libraries of pre-computed spectra.

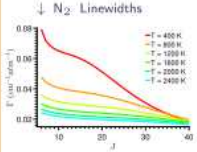
Weight Terms

$$\chi(t) = iN \sum_k \sum_{v} \sum_{\Delta J=\pm 2} W_{v,J}^{(k)} \sin(\omega_{v,J}^{(k)} t) \exp(-\Gamma_{v,J}^{(k)} t)$$

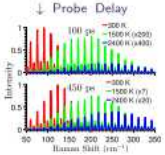
Raman Frequencies

Linewidth-dependent decay

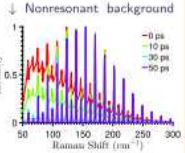
↓ N_2 Linewidths



↓ Probe Delay



↓ Nonresonant background

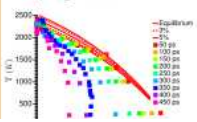


Validation Measurements

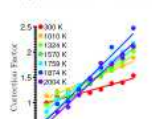
Hencken Burner

- Near adiabatic H_2-air flat flame on a Hencken Burner
- Tests with multiple equivalence ratios and probe delays
- Demonstration of robust thermometry across all probe delays
- Systematic errors with O_2 concentrations
  - Triplet state of O_2 is not in MEG model
  - Fit O_2 linewidth correction factors to Hencken burner data

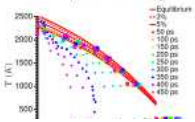
↓ O_2 Issues



↓ Correction factors

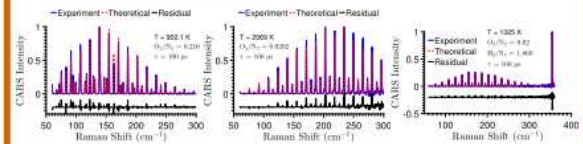


↓ Corrected O_2

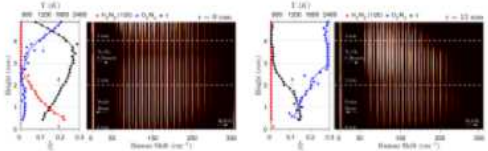


Applied to DBD burner @ 8.75 kV

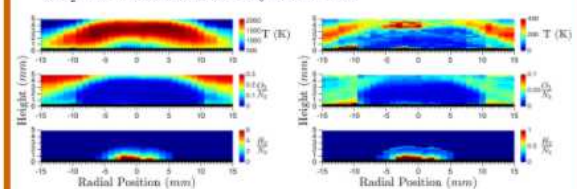
Example fits to single-shot experimental spectra using the empirically corrected synthetic libraries. Hydrogen was determined by first fitting the N_2-O_2 lines for temperature and O_2/N_2 concentrations, fixing the values, and then refitting for H_2/N_2.



Single-shot images at $r = 0$ mm and $r = 13$ mm, corresponding to probe delays of 100 and 450 ps respectively, detail the scalars of interest as a function of height above the burner surface. At $r = 0$ mm, the 100 ps was allowed by the overall higher temperatures and the region of cold gas being near the edge of the beam overlap and thus generated a lower signal in general. Farther out radially, in regions of larger temperature gradients, longer probe delays are required in order to prevent the cold, near room air gas from saturating the detector.



The average (left) and standard deviation (right) of 500 laser shots for each scalar property at each radial position is shown below in the contour plots. Average contours demonstrate this near radial jet of fuel with the highest temperature regions occurring ~4 mm off the quartz surface. Fluctuations in the reaction zone location lead to the highest deviations in temperature, whereas the largest deviations of O_2 occur at further radial locations along the burner surface.



Conclusions

- Demonstration of 1D hybrid CARS on a DBD burner
  - Simultaneous temperature and species concentrations
- Further work on the collisional dephasing of O_2 is needed
  - O_2 triplet state effects on the CARS signal decay

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