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Simultaneous imaging of fuel, OH, and three component velocity fields in high pressure, liquid fueled, swirl stabilized flames at 5 kHz[☆]

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ABSTRACT

This paper describes implementation of simultaneous, high speed (5 kHz) stereo PIV, OH and fuel-PLIF in a pressurized, liquid fueled, swirl stabilized flame. The experiments were performed to characterize the flow field, qualitative heat release and fuel spray distributions, and flame dynamics. Acquiring high speed OH-PLIF in pressurized, liquid fuel systems is difficult due to the strong overlap of the fuel's absorption and emission spectra with the OH fluorescence spectrum. To overcome difficulties associated with the overlap, the OH and fuel fluorescence signals were partially separated by using two cameras with differing spectral filters and data acquisition timing. Upon data reduction, regions containing fuel, OH and a mixture of fuel and OH are identified. Instantaneous and time-averaged results are discussed showing the flow field, flame position and dynamics, and spray distribution from the fuel signal for two multi-component liquid fuels, at two inlet temperatures and three pressures. These results are used to infer several important observations on coupled flow and flame physics. Specifically, the flame is "M-shaped" at higher preheat temperature and higher fuel/air ratio, as opposed to no visible reaction on the inside of the annular fuel/air jet at low temperature and fuel/air ratio conditions. While such fundamentally different flame topologies in gaseous, premixed flames are well known, these results show that there are also different families of flame shapes and heat release distributions in spray flames. In addition, the flame position with respect to the flow is different for the liquid-fueled flame than for gaseous, premixed flames—in premixed flames with this geometry, the flame lies in the low velocity shear layer separating the reactants and the recirculating products. In contrast, the flame location is controlled by the spray location in this spray flame, as opposed to the shear layer. For example, reactions are observed near the nozzle outlet in the core of the high velocity annular jet, something which would not be observed in the premixed flame configuration. Also of interest is the near invariance of the key flow features—such as jet core trajectory or shear layer locations—to the operating condition changes for this study, even as the spray penetration and distribution, and flame position change appreciably.

1. Introduction

Decreasing the harmful emissions from gas turbine combustors, without compromising their operational limits, requires improved understanding of internal reacting flow processes. Emissions and operational limits are influenced by (1) gas phase velocity field, (2) liquid phase fuel distribution, including droplet velocity, sizes, and morphology, (3) heat release, (4) gas phase fuel distribution and local fuel/air ratio, and (5) key scalar species distributions. These quantities can be directly tied to emissions characteristics, such as particulates, unburned hydrocarbons, and NOx, as well as operability characteristics, such as combustion instability, ignition, and blowoff. For example, gas phase fuel/air ratio distributions play important role in ignition probabilities and blowoff boundaries, while the axial heat release distribution (which is more fundamentally controlled by liquid fuel distribution, flow velocity, etc.) is an important factor in combustion instability limits.

Before discussing flow/flame physics in these combustors, we first consider basic issues and progress in the various diagnostics which can be employed. With innovations in laser systems, intensifiers, and cameras in recent years, high speed imaging for combustion research has seen a rapid increase using either short

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bursts of pulses [1,2] or sustained high repetition pulse trains [3–5]. High speed (kHz), spatially resolved imaging techniques provide important insights into these dynamic processes. High speed particle image velocimetry (PIV) systems have enabled significant improvements in understanding the morphology of unsteady, premixed, three dimensional swirling flows [3,6], while high speed planar laser-induced fluorescence (PLIF) techniques, particularly systems imaging OH radical distribution, have enabled simultaneous visualizations of the flame zone with kHz rate temporal resolution, in order to study the flow and flame physics [4,5,7–12]. Significant challenges arise, however, when making measurements in multi-phase (liquid fueled), high pressure, reacting environments. First, the cost and complexity associated with operating high pressure, high power rigs pose challenges in optimizing the setup over multiple iterations. Also, the need to image through multiple optical windows introduces additional issues, such as scattering, window fouling from soot or PIV seed particles, and optical distortions. Viewing windows, which must be able to withstand the pressurized and high temperature conditions, must also have high transmittance when performing diagnostics in the UV range. In addition, the vibrations and noise of the combustor may require the laser system to be physically separated from the test cell, requiring a longer beam path that is more vulnerable to vibrations. Finally, it is difficult to differentiate regions containing fuel from those containing OH when doing fluorescence measurements with complex fuels.

Many prior workers have reported results from high pressure, liquid-fueled, reacting PIV. Examples of such low repetition rate work are from Hochgreb's group [13,14] and researchers at DLR [15,16], and high repetition rate examples come from Slabaugh et al. [17,18]. OH-PLIF has been performed at low repetition rates in reacting flow systems with liquid fuel. Allen et al. [19] described OH-PLIF measurements on neat fuel sprays (heptane, methanol and ethanol) from 1 to 10 bar, and observed interference from polycyclic aromatic hydrocarbons (PAH) fluorescence. The PAH levels increased with pressure, similar to soot production, as also noted in other studies [20,21]. Frank et al. [22] presented 10 Hz OH fields at varying global fuel/air ratios and pressures up to 20 bar with liquid fuel. Locke et al. performed 10 Hz OH-PLIF in a swirl-stabilized fuel tube combustor with JP-8 spray at pressures up to 18 bar [23,24]. Interference from PAH was also observed in 10 Hz CH_2O-PLIF measurements with n-dodecane at 60 bar from Skeen et al. [25].

Initial work on high-speed OH-PLIF imaging in a liquid-fueled, swirl combustor employed multiple, low repetition-rate lasers to create an eight shot burst at pressures up to 13 bar [26]. Similarly, in IC engines OH-PLIF has been obtained with short bursts of pulses [27] and sustained high repetition rate imaging [28,29]. Recently, continuous (non-burst mode) high speed, simultaneous PIV and OH-PLIF has been applied to liquid-fueled combustors [17,18] and IC engines [29].

The current work focuses on simultaneous high speed stereoscopic PIV (sPIV), OH- and fuel-PLIF measurements in high pressure, liquid-fueled, swirling, reacting flows. The main challenges identified by the above studies and others with obtaining these measurements are outlined as follow. First, PIV suffers from interference caused by liquid droplet scattering, as the droplets may be brighter than the seeding particles. This produces a measured velocity bias as large droplets may not follow the flow well. Two options are to mask out the region of spray from the PIV fields [15,16] or attempt to separate the spray and seeding particles before PIV processing [17,18]. In the present work we employ a new approach along the lines of the latter, by using simultaneous PLIF data to identify gaseous and liquid spray regions in the PIV images, thus, enabling calculation of conditioned gaseous velocity fields and liquid velocity fields.

Next consider LIF measurements. Some key challenges associated with OH-LIF in high pressure, liquid fuel combustion are [30–33]: (1) reduction of fluorescence yield due to increase in collisional quenching (mitigated somewhat by increase in number density); (2) collisional broadening (decay in strength of spectral lines) and overlap of the excitation lines, (3) fluorescence trapping due to the increased optical density at high pressure, (4) laser energy absorption by liquid fuel and higher gas concentration, and (5) interference from liquid fuel and unburnt hydrocarbon fluorescence resulting from fuel decomposition.

High speed measurements add further complications, as the excitation energy (per pulse) is reduced substantially. A typical high speed dye laser system has pulse energies in the ~100 µJ range, compared to ~10 mJ for low speed Nd:YAG-pumped dye lasers and optical parametric oscillators (OPOs), and ~100 mJ for tunable excimer lasers [19]. We note that pulse-burst laser systems are becoming increasingly useful for high energy, high to ultra-fast (MHz) repetition applications, albeit suffering from a low number of laser pulses (low hundreds). For PLIF applications pulse-burst lasers can be used to pump OPOs at ~10–50 kHz rates for pulse energies up to ~100 mJ [34–36]. The high pulse energy of the lower repetition rate and pulse-burst systems produces better contrast in the fluorescence signal, compensating for the losses associated with fluorescence quenching (challenge 1 above), trapping (2), and laser energy depletion. In practice, the interference from fuel and other hydrocarbons (4) are the most critical issues, as shown in the earlier high speed imaging work in similar flames [26] and require specialized detection and post-processing schemes discussed in this work.

Despite these difficulties, the simultaneous deployment of such flow and scalar measurements clearly enables significant insights into the structure of the coupled flow, spray, flame, and other scalars such as pollutants, which would not be possible if the measurements were made in isolation. Furthermore, these insights can materially differ when the measurements are in aero engine relevant conditions vs. conditions more conducive to optical diagnostics (such as low pressure conditions). For example, such measurements are now routinely used in the engine community to provide insight into flame-flow-spray interactions. For example, Peterson and Sick [29] utilized simultaneous PLIF, PIV, and spark energy measurements in an optical engine to show that spark energy observed linearly increased with shear strain rate. Skeen et al. [25] presented simultaneous formaldehyde PLIF (requiring techniques to separate the fluorescence from polycyclic aromatic hydrocarbons, PAH, from the formaldehyde, as discussed above) and Mie scattering to show that low temperature reactions initiate on the radial edges of the spray and forms rapidly near the injector after the end of injection. Müller et al. [28] presented OH-PLIF measurements in an optical engine with variable valve timing, showing the pronounced slowing of flame kernel growth after ignition as exhaust gas recirculation levels increased.

Similarly, simultaneous PLIF and PIV measurements are now standard measurement approaches for understanding thermoacoustic instabilities in swirl burners. These measurements clearly demonstrate that the structure of these flows are strongly three-dimensional, being dominated by large scale helical flow structures and precession of flow/flame features. As such, application of, for example, line of sight chemiluminescence measurements alone is of limited value in understanding flame-flow interactions. For example, Steinberg et al. [5] presented simultaneous PIV, OH-PLIF, and OH*[1] chemiluminescence in a thermoacoustically unstable swirl burner and were able to show how the interactions

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[1] OH* denotes the chemically excited OH radical, whose chemiluminescence is used to visualize the flame.