Sub Topic: Soot and Other Combustion-Generated Aerosols

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Framing Camera Time-resolved Laser Induced Incandescence Measurements in a Rich Quench Lean Combustor

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Abstract: Determining the size of soot particles in dynamic turbulent flames is critical for optimizing injector and combustor designs. In this work, we demonstrate the first use of a gigahertz-rate framing camera for planar time-resolved laser-induced incandescence (TiRe-LII) measurements in a rich quench lean (RQL) combustion system with Jet A fuel. In this method, the framing camera is able to capture the background luminosity, prompt LII signal, and temporal incandescence decay at up to 40 MHz. This enables shorter time constant fits than any prior 2D TiRe-LII experiments, enhancing confidence in soot particle size and soot volume fraction estimates. Measurements are performed at a preheat temperature of 600 K, pressures ranging from 59 to 120 psig, and equivalence ratios from 0.26 to 0.29. Initial results show clear soot volume fraction and particle size changes with pressure and equivalence ratio.

Keywords:* *High Pressure Combustion, Rich Quench Lean, Soot Particle Sizing, LII

1. Introduction

Soot is the primary constituent of non-volatile particulate matter (nvPM), and has been studied intensely with aims to reduce emissions. Reducing soot also helps increase engine efficiency and component lifetime by reducing black-body thermal loading on engine hardware. Laser-induced incandescence has proven to be a powerful diagnostic for quantifying in-situ soot distributions in many combustion processes [1–3]. Despite the value of this diagnostic, there are few studies at conditions relevant to aeroengine operation [4–6]. High pressures, in particular, lead to more limited optical access and faster incandescence decay times [5, 7], which can be challenging to capture with traditional high speed cameras.

To overcome these limitations, this work presents the first use of a gigahertz-rate framing camera for TiRe-LII measurements in a rich quench lean (RQL) combustor using Jet A fuel. This technique enables the background emission, prompt LII signal, and incandescence decay to be captured across multiple frames at a rate of up to 40 MHz, which is faster than any prior imaging TiRe-LII system. The combustor design is first described followed by the layout of the TiRe-LII system. Then, experimental results for an air preheat temperature of 600 K, pressures of 59 to 120 psig, and global equivalence ratios of 0.26 to 0.29 are demonstrated.

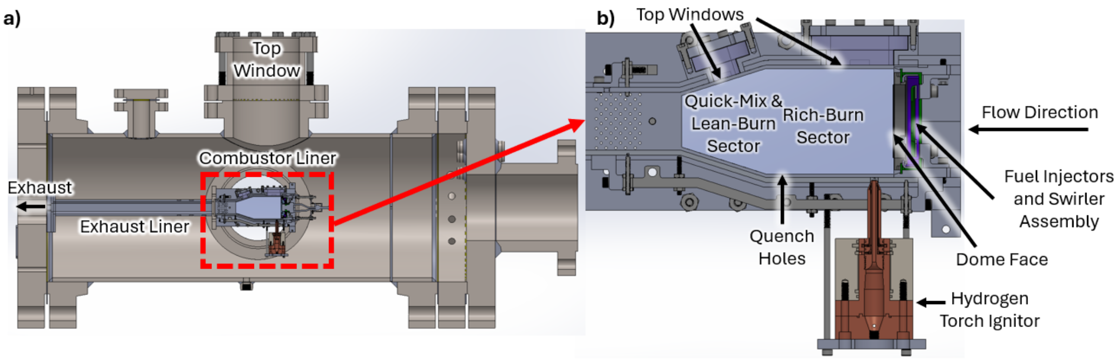

Figure 1: a) Section view of the pressure vessel, combustor liner, and exhaust liner cantilevered to the back exhaust flange are shown. Optical access from the top windows of the pressure vessel and combustor are used for LII imaging and the side windows are used for the LII laser sheet. b) Magnified section view of the RQL combustor liner shows the fuel injectors, swirlers, torch ignitor, and quench holes.

2. Rich-burn Quick-mix Lean-burn Combustor Architecture

A diagram of the Georgia Tech RQL combustor is shown in Fig. 1 with flow moving from right to left. Here, the multi-sector dome face uses three inlets for fuel injection, each surrounded by swirling air vanes for flow recirculation and flame anchoring. Jet A fuel for the injectors is delivered from a 208 L (55 gal) tank and driven through a Parker piston accumulator pressurized with nitrogen. The fuel mass flow is then controlled by a series of valves and Bronkhorst Corilois flow meters. Jet A fuel is then sent into the pressure vessel through a squeeze flange and insulated manifold into the triple-injector dome face. In this work, only the central injector is supplied with fuel while air is supplied to all of the swirl vanes.

To start the combustion process, a hydrogen-air torch ignitor and glow plug assembly located at the bottom of the combustion liner are utilized. Once the flow from the injectors ignites, the ignitor is de-energized and the fuel-rich mixture burns in the upstream region. Downstream, in the quick-mix and lean-burn region, quench air is introduced to the flow through a line of large holes in the combustion liner [5]. This mixing forces a globally lean equivalence region. Two windows are added to the top of the combustion liner for capturing the LII signal and two different side windows are placed on the combustion liner for passing the laser sheet. The pressure vessel also has three 10 inch diameter windows made of fused quartz for optical axis, one top and two sides. To cool the combustion liner and keep each of the windows clear of soot, effusion cooling holes are placed throughout the liner walls and along the inside edges of each window. After the combustion liner, the flow enters the custom water-cooled exhaust section before exiting the pressure vessel through choke plates placed at the exhaust flange.

2.1 Time-resolved Laser-induced Incandescence

Time-resolved laser-induced incandescence is used in this work to study the soot volume fractions and soot particle sizes formed in the rich-burn sector of the combustor. This optical diagnostic passes a high-fluence laser sheet through the combustor to rapidly heat soot particles. The temporal decay of soot incandescence is then imaged by an ultra-high speed intensified framing camera. Filters are used to eliminate laser scattering and transmit the broadband incandescence signal to

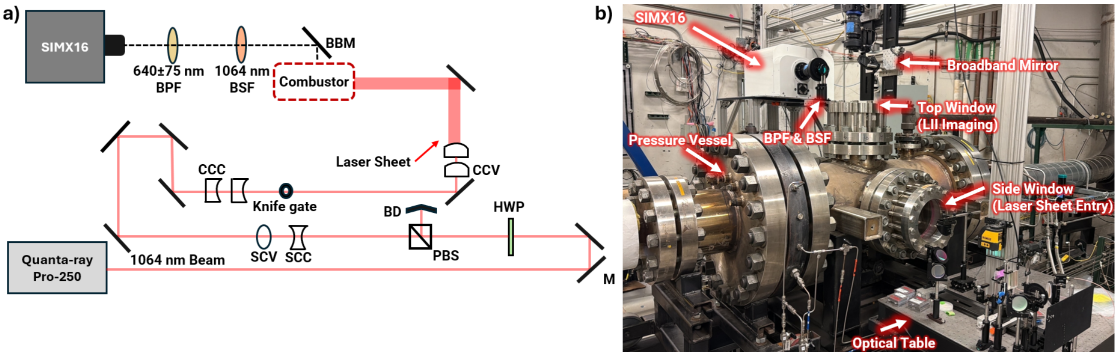

Figure 2: a) Optical layout for the TiRe-LII diagnostic is shown. The following abbreviations are used: M (mirror), HWP (half-wave plate), PBS (polarizing beam splitter), BD (beam dump), SCC (spherical concave lens), SCV (spherical convex lens), CCC (cylindrical concave lens), CCV (cylindrical convex lens), BBM (broadband mirror), BS (bandstop filter), and BP (bandpass filter). b) A photograph of the optical setup is also shown in high pressure test cell.

the camera sensor. Due to severe extinction observed when the laser sheet is passed through the flames from all three injectors, this work is performed using only the center injector.

For this diagnostic, a Spectra Physics Quanta-Ray Pro-250 Nd:YAG laser with a 1064 nm output is used to heat the soot particles. The beam first goes through a half wave plate and polarizing beam splitter to adjust intensity. The beam is then passed through two spherical lenses to collimate the beam. Next, cylindrical lens pairs are used to expand the beam in one direction and compress and collimate the beam in the other direction to create the laser sheet that is passed through the combustor windows. The optical layout for the TiRe-LII system is shown in Fig. 2. The fluence for these measurements is approximately 0.35 $\mathrm{J/cm^2}$, which is near the LII saturation intensity used in prior work [5].

To image the incandescence signal, a Specialised Imaging SIMX16 intensified camera (12-bit, 6.45 µm pixel size) is used. Here, ten of the sixteen available channels are timed such that each set of successive frames have similar initial exposure and duration times. This enables image stacking to increase the signal-to-noise ratio and results in five frames (resolution of 1280 x 960 pixels) captured at different time for estimating the soot intensity decay. To prevent reflections and attenuate signal from Swan band emissions, a 1064 nm notch filter and 640 ± 75 nm bandpass filter are used. A large aperture Rokinon lens is mounted to the camera (focal length of 85 nm and $F1.4$) in order to maximize light collection and increase the signal-to-noise ratio. The camera is positioned such that central injector is centered in the field of view. Due to geometric and weight constraints, the SIMX16 camera is not mounted directly perpendicular to the flow direction through the injectors. Instead, a broadband mirror is mounted directly above the combustor and angled such that the reflected flame emissions are visible on the camera.

3. Experimental Results

Preliminary experimental data is captured at a vessel temperature of 600 K for vessel pressures between 58.8 and 120 psig. The global equivalence ratio is also varied while maintaining vessel temperature. At each condition, a background image is first captured, providing information on the broadband flame radiation in the absence of the laser pulse. Then, a subsequent image is

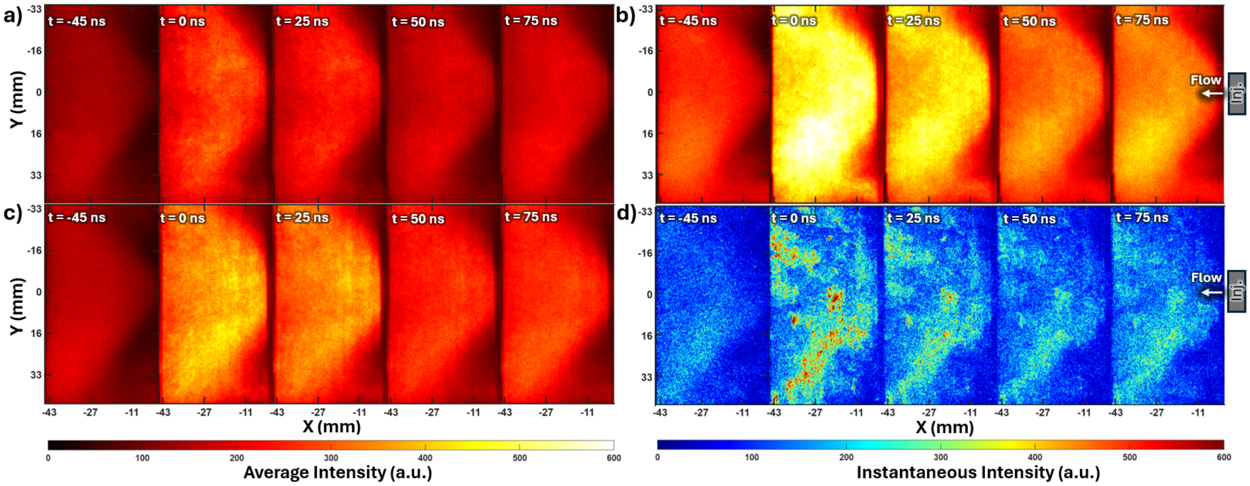

Figure 3: Mean TiRe-LII images are captured with the framing camera and show the background image, prompt LII signal, and subsequent temporal decay with 25 ns delays between each subsequent image. The temperature is constant at 600 K and the conditions for a) P = 58.8 psig, $\Phi = 0.26$, b) P = 120 psig, $\Phi = 0.26$, and c) P = 58.8 psig, $\Phi = 0.29$ are shown. d) An instantaneous LII image at the condition in a) shows turbulent flame structures. Flow in this image advances from the right to the left in each sub image. The x dimension is distance from the dome face, y is distance from the injector centerline, and color is the intensity in arbitrary units.

captured when the laser pulse arrives at the combustor, and is considered the prompt LII signal at $t = 0$ ns. In subsequent frames each delayed by 25 ns (40 MHz sampling rate with 20 ns exposure), the temporal incandescence decay is observed as each image becomes progressively dimmer approaching the background intensity. By tracking the intensity decay on a per-pixel basis, the LII signal can be fit to a calibrated exponential decay LII model for Jet A fuel in order to estimate particle size [2]. For each test condition, 50 sets of instantaneous images are captured. The ensemble-averages shown in Fig. 3 represent the mean field and turbulent flame structures can be seen for each individual data set.

From these results, it is clear that the prompt LII signal, which scales linearly with the soot volume fraction, increases with higher equivalence ratios as shown in Fig. 3(a) and (c). This implies that soot production is favored in richer environments where there is less oxidation. Similarly, an increase in prompt LII signal is observed as pressure is increased, as shown in Fig. 3(a) and (b). This implies that soot production is favored at higher pressures as number density increases, which further drives collision rates and PAH formation. These results also show a fast decay in the incandescence signal that is visibly dimmer at 50 ns. This indicates the presence of small soot particles that could not be captured with slower ultra-high speed cameras that have a maximum frame rate of 10 MHz or inter-frame time of 100 ns [1, 2, 5].

4. Conclusions

In this work, we demonstrate the first application of a framing camera for time-resolved laser-incandescence in a RQL aeroengine combustor. While previous work used cameras with a maximum sampling rate of 10 MHz, this sampling rate is too slow for capturing the fast incandescence decay times observed in high pressure combustion systems. By using a gigahertz camera, tracking of the temporal decay process can be significantly improved. This allows for better exponential decay model fitting and reduces uncertainty in extracting time constants and particle sizes estimates.

Next steps for this work include fitting decay constants to each pixel of each data set and comparing the measured decay constants with calibrated soot particle size models. These results can then be compared with NvPM concentrations measured at the combustor exhaust via a gas sampling probe. At the same time, planar laser-induced florescence data targeting PAH and OH can be used to help understand the relationship between soot formation, oxidation, and the flow turbulence in this multi-sector combustor at relevant aeroengine operating conditions.

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