The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Laser Diagnostics for Investigating Turbulent Combustion Phenomena in a Model Scramjet

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Abstract

Investigating turbulent combustion phenomena occurring in a scramjet combustor is extremely challenging. This is because the turbulent flow and flame structures in the supersonic internal flows are inherently three dimensional and evolve rapidly. Therefore, 3D simultaneous measurement with high spatial and temporal resolutions is essential to fully resolve the turbulent combustion phenomena. Nevertheless, currently available measurement techniques including the most cutting-edge laser diagnostics tools still have severe limitations in resolving the high-speed combustion phenomena. Recently, 3D flame/flow visualization techniques and quantitative nanosecond laser induced breakdown spectroscopy method have been developed for effectively resolve the complex flow/flame behaviors. Some sample diagnostics results utilizing the new tools to visualize the 3D scramjet flow/flame structures and to measure 2D local concentration and gas density fields will be introduced in the presentation.

Introduction

Visualizing flows and quantifying properties in high-speed compressible reacting environments of scramjets are challenging, but essential for understanding the physicochemical phenomena occurring in the high-speed turbulent flows. Insertion of physical probes and implementation of sensors on surfaces will induce shockwaves and alter the flow fields significantly, thus the use of most conventional visualization and measurement techniques are limited under the scramjet relevant flow conditions. Alternatively, non-intrusive optical measurement methods have been used in the high-speed environments. Among the various optical techniques successfully instrumented in the harsh flow environments, a few representative optical methods visualizing the flow/flame structures and quantitatively measuring flow properties that have been intensively used in our research group will be presented. Condensed carbon dioxide induced Rayleigh scattering (Planar Laser Rayleigh Scattering, PLRS), planar laser-induced hydroxyl radical fluorescence (OH PLIF), and nanosecond Laser Induced Breakdown Spectroscopy (n-LIBS) were used for flow/flame visualization and simultaneous fuel concentration and gas density measurements, respectively.

Experimental Setup

An arc-heated hypersonic wind tunnel (ACT-1) at University of Notre Dame (Fig. 1), a continuous supersonic wind tunnel of research cell 19 (RC-19) at Wright Patterson Air Force Base (WPAFB) were used for providing the scramjet relevant flows. In ACT-1, a small scale model scramjet (Fig. 2) was installed for combustion tests in an integrated scramjet vehicle system, and a model scramjet combustor with a cavity of direct fuel injection was used in the RC-19 supersonic tunnel.

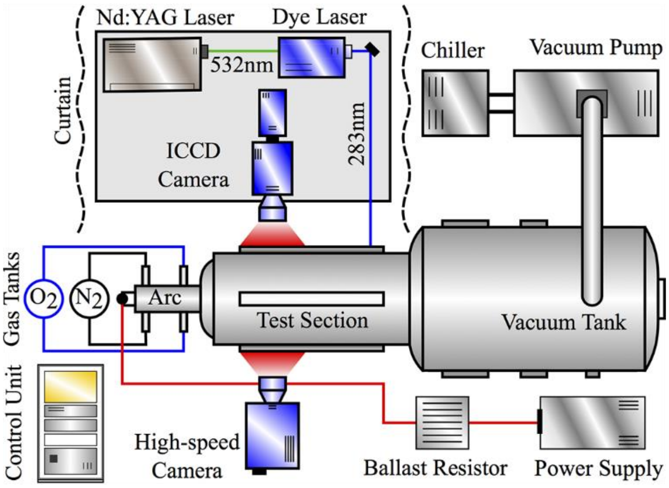

Fig. 1 ACT-1 at University of Notre Dame

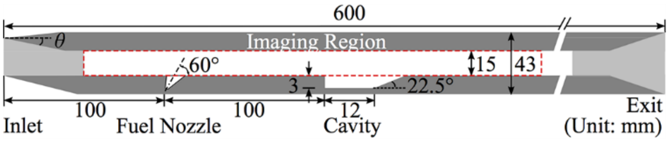

Fig. 2 A section view of the model scramjet at the central plane along the flow direction

The ACT-1 was designed to produce high-enthalpy and high-Mach number freestreams with one-second run time for supersonic combustion tests [1]. The facility having an open-test section was designed for hypersonic combustion tests and uses a sequential gas feeding system before/after the plasma arc heater to reduce NOx production in freestreams that affect combustion dynamics. The arc heater is connected to a 260 kW DC power supply delivering current of 430 A to produce flows of up to 6 MJ/kg and 1 MPa at the stagnation condition. The test condition is repeatable within 2% variations in stagnation pressure and arc current/voltage.

The laser radiation for PLRS was generated using a 10-Hz Nd:YAG pulsed laser (Spectra-Physics, Model Quanta-Ray Pro-250) at 532-nm (13 mJ per pulse) to illuminate the imaging area of the flow field. A 16-bit intensified charge-coupled device (ICCD) camera (Imager Pro X and LaVision IRO Intensifier) was used to record the scattered laser radiation with a 100-ns gate width. For the OH PLIF, the same Nd:YAG laser was used to pump a tunable dye laser (Sirah, Model PRSC-D-24) for producing radiation at 566 nm that was then frequency-doubled to produce 283-nm radiation (with pulse energy of 13 mJ). The 283-m 2D planar laser sheet is used to excite ground-state OH radicals via the Q1(7) transition of the A2Σ+–X2Π(1,0) band [19].

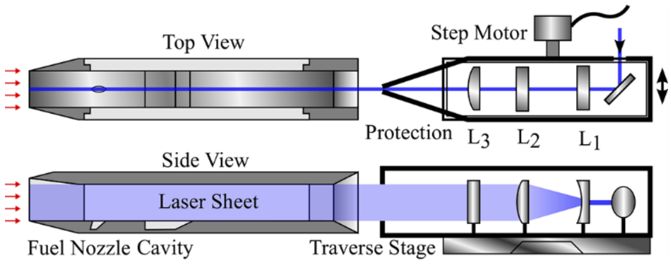

Fig. 3 An optical transformation system in ACT-1.

An optical transformation system (Fig. 3) is used to spread a thin circular laser beam into a planar laser sheet that was injected into a model scramjet in the counter-streamwise direction. As shown in Fig. 3, a laser beam was directed into the beam transformation system through a hole on the enclosure to be redirected toward the model scramjet exhaust, and then expanded into a 15-mm-height thin sheet parallel to the model scramjet centerline. The optical system is on an automated translation stage, which enables the laser sheet scanning over the entire flow volume along the transverse direction for instantaneous two-dimensional (2D) flow-field (PLRS) and flame-structure (OH-PLIF) visualizations.

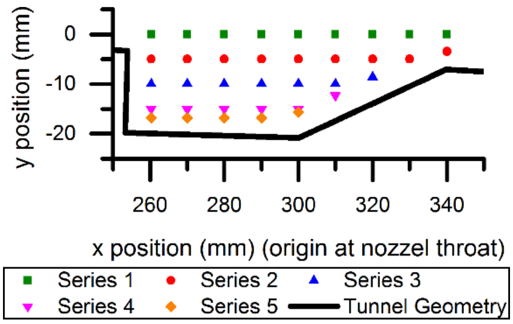

Fig. 4 Geometry of the cavity flameholder in the RC-19 model scramjet combustor. n-LIBS measurement locations are indicated (series 1 – 5).

Another experimental setup for the n-LIBS measurements was built around the RC-19 continuous supersonic wind tunnel that accommodates a flow path of 152.4 mm in width and a cavity flameholder as seen in Fig. 4 [2]. Mach 2 and 590 K static temperature air flows (from left to the right in Fig. 4) were used for the tests. Ethylene fuel injection holes on the inclined cavity ramp wall supply fuels into the primary recirculation zone of the cavity for sustaining combustion reactions being mixed with the entrained air from above the cavity in the freestream.

A 532-nm, Q-switched Nd:YAG laser (Spectra Physics GRC-170) operating at 10 Hz was used to induce breakdown for n-LIBS measurements in RC-19. The focal length of the focusing lens was 17.5 cm. The lens was located outside of the model scramjet combustor to inject a converging laser beam into the designated locations (see Fig. 4) through a fused-silica optical access window. A fast spectrometer (Kaiser HoloSpec f/1.8) and a camera (Andor iStar DH320T-18U-73) located at the spectrometer exit plane captured the plasma emissions.

Results

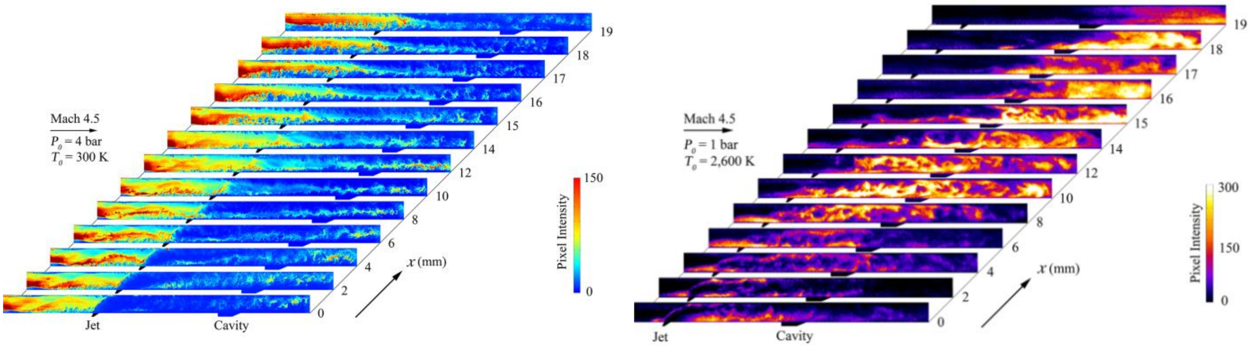

Fig. 5 3D flow (PLRS, left) and flame (OH PLIF, right) structures in a model scramjet of ACT-1.

Figure 5 shows the 3D flow and flame structures resolved utilizing the PLRS and OH PLIF. The freestream condition was Mach 4.5 in both cases, thus the flow is inherently turbulent and three dimensional. Figure 6 shows a top view of the 3D flow structure reconstructed from the 3D PLRS images, which is consistent with the 3D flame structure resolved by the OH PLIF images. In the slow flow and high static temperature side wall boundary layers, the flame further advances toward the inlet, and the strongest combustion reaction was observed in the fuel-air mixing region behind the jet injection location.

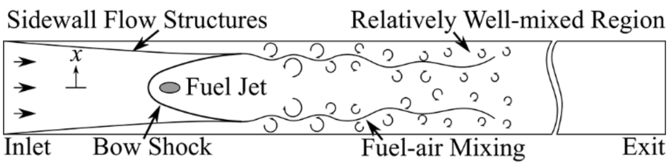

Fig. 6 Top view of the 3D flow structure reconstructed from the 3D PLRS images.

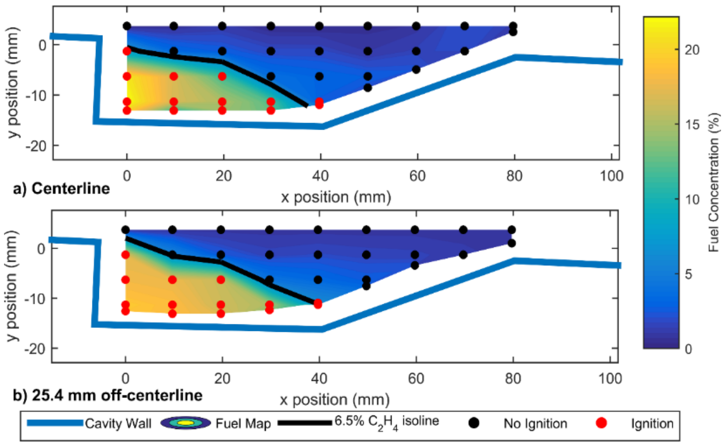

Fig. 7 Ethylene concentration fields on the centerline and 1 inch off-centerline measured using the n-LIBS.

Figure 7 presents sample results of the n-LIBS measurements in RC-19. High-accuracy concentration and density measurements were successfully done utilizing a novel Direct Spectrum Matching (DSM) method in conjunction with the n-LIBS [3]. The laser induced breakdown plasma is also capable of igniting a cavity flame, and a new method for quantifying the ignition probability at the locations of the plasma was developed. Red dots in Fig. 7are ignitable locations while the black dots represent non-ignitable locations in the cavity flameholder due to low fuel concentration, high-stretch rate near the shear layer, and/or steep concentration gradients.

Summary

3D flow and flame visualization and quantitative fuel concentration and gas density measurements were conducted in high-speed turbulent reacting environments. In order to resolve the inherently three dimensional flow/flame structures and uncorrelated flow properties in turbulent environments, novel methods for non-intrusive optical measurements (3D PLRS/OH-PLIF and n-LIBS) were developed and tested in scramjet relevant flow conditions.

Acknowledgement

This work was supported by the American Society for Engineering Education (ASEE), through the Summer Faculty Fellowship Program (SFFP), the Air Force Research Laboratory (AFRL), and the Air Force Office of Scientific Research (AFOSR, FA9550-12-1-0161).

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