Combustion and Flame 000 (2016) 1–12

Contents lists available at ScienceDirect

Combustion and Flame

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

Raman scattering measurements of mixing and finite-rate chemistry in a supersonic reacting flow over a piloted, ramped cavity

Nathan R. Grady[a,*], Robert W. Pitz[a], Campbell D. Carter[b], Kuang-Yu Hsu[c]

[a] *Mechanical Engineering Department, Vanderbilt University, Nashville, TN 37235, United States*
[b] *U.S. Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433, United States*
[c] *Innovative Scientific Solutions, Inc., Dayton, OH 45459, United States*

ARTICLE INFO

Article history:
Received 24 August 2015
Revised 14 December 2015
Accepted 15 December 2015
Available online xxx

Keywords:
Raman
Scramjet
Cavity
Supersonic
Diffusion
Combustion

ABSTRACT

UV Raman scattering is applied to measure fuel/air mixing and combustion of a Mach-2 air stream flowing over a step-ramp cavity fueled with 70% methane/30% hydrogen. Average and RMS fluctuations of temperature and major species profiles as well as scatter plots of simultaneous temperature and chemical scalars are determined from single-shot Raman scattering measurements along a 6-mm line transverse to the main supersonic flow. In the fuel-rich regions of the pilot cavity, the 248-nm KrF laser induces broadband fluorescence interference that reduces the number of analyzable Raman spectra; nonetheless, on the whole, a significant fraction of the spectra were reducible. In the cavity, hydrogen fuel reacts quickly resulting in a uniform water concentration in the recirculation zone. Methane reacts slowly to carbon monoxide/carbon dioxide in the cavity, leading to non-uniform concentrations of these species. Mean and instantaneous mixture fraction data inside the shear layer were indicative of oxygen transport across the shear layer. Temperature, water, and oxygen fluctuations are fairly constant throughout the combustor due to recirculation/turbulent transport across the shear layer and the slow reaction of methane.

1. Introduction

The current Reynolds-Averaged Navier–Stokes (RANS) simulation codes used to design scramjet combustors use simplified physical models in order to calculate the complex geometry with detailed chemistry and unsteady compressible turbulent flow. While these models generally provide guidelines for future experimental efforts, they fail to capture the phenomenological flow patterns. Therefore, the use of large-eddy-simulation (LES), which promises to give improved prediction of turbulent combustion [1,2] in supersonic flows [3], has been proposed. LES is more computationally efficient than direct numerical simulation (DNS), because in LES only the large-scale features that contain the bulk of the kinetic energy are computed. LES requires subgrid closure methods to model events that occur below the grid resolution for momentum, energy, and scalar transport. Previous comparisons of numerical and experimental data by Grady et al. [4] have demonstrated the accuracy of LES to predict the flow patterns over a ramp close-out cavity under nonreacting conditions, validating subgrid closure methods for both momentum and energy transport. However, in order to validate and/or improve scalar transport closures, which model chemistry and its interaction with turbulence such as those detailed in a review paper by Gicquel et al. [5] (e.g. probability density function, flamelet, linear-eddy mixing, neural networks, etc.), reacting flow data are needed. Of particular interest, is the ability of reduced chemical mechanisms to accurately predict the behavior of multi-component fuels (e.g. cracked jet fuel that have components with a wide range of reactivity) in complex geometries and flows. However, modeling jet fuel even with a reduced mechanism is computationally expensive and may have a large uncertainty. As an alternative to modeling jet fuel, a surrogate fuel with simpler chemistry can be used to facilitate simulations and still capture turbulence-chemistry interactions; however, experimental data is needed for these conditions.

In order to verify the ability of these numerical models to predict turbulence-chemistry interaction or assess the validity of reduced chemical kinetics, in situ and temporally resolved experimental measurements of temperature and species are needed in compressible flows with realistic combustors. O'Byrne et al. [6] have performed extensive coherent anti-Stokes Raman scattering (CARS) measurements of temperature and O_2, N_2, and H_2 mole fractions in a model scramjet combustor fueled with H_2. [7–9]. Additionally, Fulton et al. [10] compared LES/RANS simulations to

---

[*] Corresponding author.
E-mail address: nrgrady@gmail.com, grady.346@osu.edu (N.R. Grady).

http://dx.doi.org/10.1016/j.combustflame.2015.12.014

Please cite this article as: N.R. Grady et al., Raman scattering measurements of mixing and finite-rate chemistry in a supersonic reacting flow over a piloted, ramped cavity, Combustion and Flame (2016), http://dx.doi.org/10.1016/j.combustflame.2015.12.014

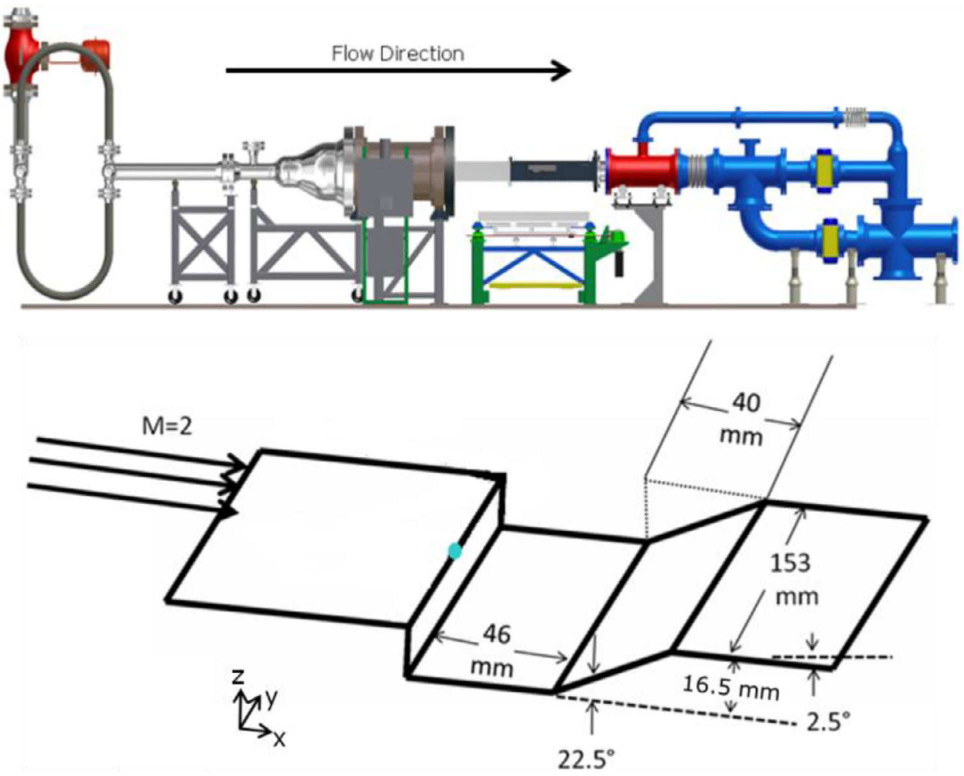

Fig. 1. Research Cell 19 wind tunnel schematic (top), and close-up of combustor and cavity (bottom) with the blue dot located on the leading edge of the cavity and the centerline of the combustor ($x = 0$, $y = 0$, $z = 0$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

CARS measurements of temperature, and O_2, N_2, and H_2 concentrations in supersonic combustion behind a step. Of course, in a hydrocarbon-fueled combustor, measurement of all the major species is a challenge for CARS (although new developments have been demonstrated [11,12]). Spontaneous Raman scattering can satisfy this requirement (to measure all major species) using only a single laser. A detailed description of Raman scattering is given by Barlow et al. (see Chapter 14 of [13]). Previously, Raman scattering has been used in enclosed subsonic combustors by Meier and colleagues [14–16], in open supersonic jets by Cheng et al. [17], and in supersonic combustors without reaction by Carter and colleagues [18,19]. However, to the authors' knowledge, Raman scattering has not been used in a supersonic, reacting wind-tunnel. In this application UV vibrational Raman scattering, based on a KrF excimer laser with 248-nm excitation, is employed instead of visible Raman scattering for the following reasons: (1) scattering cross sections in the UV are significantly larger than those in the visible, and therefore single-shot scattering signals are relatively large (for the same laser pulse energy); and (2) the ~20-ns KrF laser pulse does not require pulse stretching to avoid dielectric breakdown.

Of course, flows within a supersonic combustion ramjet or scramjet have low residence times. Wall cavity flameholders are perhaps the simplest means of providing (1) adequate residence time, (2) reliable flameholding across a wide range of flight conditions, and (3) modest drag penalty [20]. Furthermore, wall cavities within two-dimensional flowpaths can be designed to include unobstructed optical access and offer a canonical flow that can easily be modeled [4]. Previous experiments by Gruber et al. [21] and Rasmussen et al. [22] have shown that direct fueling from the rear of the cavity supports combustion over a wider range of conditions and a more uniform fuel-air mixture with longer residence times than fueling from either passive entrainment or the floor of a cavity. Furthermore, there is a large database of experimental results with this configuration [21–25], so this fueling strategy was implemented in this study.

UV spontaneous Raman scattering measurements over a ramp-closeout wall cavity flameholder fueled from the ramp will be presented in this paper. Mean, root-mean square, RMS, fluctuation, and scatter plots of temperature, species concentration, and mixture fraction will be discussed. In addition, analysis of local fuel consumption and product formation will be provided.

2. Experimental system

The experiments were conducted at the supersonic flow facility in Research Cell 19 at the Aerospace Systems Directorate, Wright-Patterson Air Force Base. The wind-tunnel employed a 2-D Mach-2 nozzle with an air flow rate of 3.1 kg/s. A schematic of the wind-tunnel and test section can be found in Fig. 1. The coordinates given in this paper are in reference to $x = 0$ being on the step in the axial direction, $z = 0$ being on the step in the vertical direction, and $y = 0$ being centered on the spanwise centerline. An isolator of constant cross section (51-mm high by 153-mm wide) was upstream of the test section. There was a 2.5° expansion of the test section floor. Flame holding was provided by a cavity, which was 16.5-mm deep for 46-mm before ascending back to the test section floor at a 22.5° angle. Fused-silica windows (Esco S1-UV), located on the sides and top of the test section, allowed optical access.

The tunnel supplied heated (via a natural-gas-fueled heat exchanger), compressed air ($T_0 = 590$ K, $P_0 = 415$ kPa) continuously that was expanded to Mach-2 conditions at the isolator ($T = 330$ K, $P = 53$ kPa) and was further expanded due to the 2.5° divergence of the test-section floor ($T = 300$ K, $P = 39$ kPa). It should be noted that these wind-tunnel conditions relate, roughly, to a Mach-4 scramjet flight condition; however, the resulting static temperature in the cavity region, ~300 K, is much lower than at flight conditions. Facility limitations (seals, etc.) prevented use of

Please cite this article as: N.R. Grady et al., Raman scattering measurements of mixing and finite-rate chemistry in a supersonic reacting flow over a piloted, ramped cavity, Combustion and Flame (2016), http://dx.doi.org/10.1016/j.combustflame.2015.12.014