Raman Scattering Measurements of Mixing and Finite-Rate Chemistry in a Supersonic Reacting Flow over a Piloted, Ramped Cavity

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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.

Keywords: Raman, Scramjet, cavity, piloted, supersonic, diffusion, combustion

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 access 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 O₂, N₂, and H₂ mole fractions in a model scramjet combustor fueled with H₂. [7-9]. Additionally, Fulton et al. [10] compared LES/RANS simulations to CARS measurements of temperature, and O₂, N₂, and H₂ 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. [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 **Figure 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 higher, more realistic temperatures. Furthermore, the tunnel components (made of carbon steel) are not water cooled, and therefore run times, typically 30 seconds, were limited by the heating of the cavity (particularly the ramp). The fuel used for this study was composed of 70% methane (CH_4) and 30% hydrogen (H_2), by volume, and was premixed by the manufacturer; it was intended to represent the reactivity of a vaporized hydrocarbon jet fuel but also to minimize fluorescence interference (a primary concern with the Raman scattering technique). We note too that CH_4 and H_2 are two components expected in a cracked jet fuel; other expected gaseous components include ethane (C_2H_6) and ethylene (C_2H_4). The fuel was injected parallel to the cavity floor from the cavity close-out ramp, from the locations shown in [Figure 2](#), at a rate of 102 standard liters per minute (referenced to 273 K and 1 standard atmosphere), which is equivalent to a mass flow rate of 0.90 g/s. The fuel was passed through a manifold and split between the 11 fuel injectors, as shown in [Figure 2](#). The exit velocity of the fuel can be estimated using continuity and assuming that the density of the fuel at the jet exit can be approximated using the cavity static pressure and the room temperature:

$$V_{exit} = \frac{\dot{m}/11}{\rho_{exit} * A_{exit}} \approx \frac{\dot{m}/11}{\left(\frac{P_{cavity}}{R_{mix} * T_{room}}\right) A_{exit}}$$

where the room temperature (293 K), injector exit area (3.08 mm^2), R_{mix} (702.7 J/kg*K), and the cavity static pressure (~ 37 kPa), resulting in a velocity of ~ 150 m/s ($M_{fuel} < 0.3$).

A narrowband Lambda Physik Compex 150 KrF excimer laser (350 mJ/pulse, 20-ns pulse length) produced 248-nm radiation that was used to excite the vibrational Raman transitions. The laser was tuned away from O_2 and OH laser-induced fluorescence (LIF) transitions to reduce interference with the Raman lines. In order to prevent damage to the fused-silica wind-tunnel windows, following the procedure used by Wehr et al. [26], two 200-mm focal length, cylindrical lenses, oriented 90° from each other, were used to focus the 248-nm beam. Additionally, a thin-film polarizer was placed before the lenses to reject any unpolarized laser radiation. The laser-beam energy measured after the lenses was ~ 200 mJ/pulse. Using burn patterns, the probe size was estimated to be 0.75 mm in the x-direction and 1.5 mm in the z-direction (see Fig. 1 for the coordinate system). Raman scattering was collected through the top wind-tunnel window, collimated, and then focused onto the entrance slit of a Horiba iHR320 spectrometer using two 5-cm-diameter f/4 UV achromats, as shown in [Figure 3](#); a 6-mm-long region of the beam was imaged, but only a 5.25-mm-long segment was used for data processing. An n-butyl acetate liquid filter was placed before the entrance slit to block scattering at 248 nm. Raman signals were recorded with a PIMAX Superblue ICCD (1024 x 256 pixels, full frame, with a 25-mm intensifier) camera at a 10-Hz frequency, matching the pulse-repetition rate of the excimer laser. The photocathode was gated at 200 ns, and to further reduce background noise, multichannel plate gating was also used. The optics directing the 248-nm beam to the test

section were arranged such that the probe region could be translated vertically and axially via a remote-controlled breadboard translation table.

Bottom-wall pressures along the combustor centerline are shown in [Figure 4](#); the pressures measured upstream of the cavity are near the predicted isentropic value of 39 kPa. The drop in pressure at the fourth data point, $x = 120.4$ mm is indicative of flow separation after the ramp (c.f. Figure 5b [20]). Pressure measurements on the cavity floor ($x = 0 - 40$ mm) varied $<1\%$ during each dataset, so pressure was assumed to be constant during each dataset. Therefore, the ideal-gas law was invoked to determine the temperature using the calculated number densities of the major species and the pressure at x determined *via* linear interpolation of the cavity wall pressure measurements (i.e. the second and third probe locations at $x = 1.2$ cm and 3.8 cm, respectively, as shown in [Figure 4](#)). Since the number densities are in turn a function of temperature, the temperature was determined via an iterative scheme until convergence of ± 10 K was met. The RMS temperature fluctuation values were 9 % in the freestream, where the true variation is expected to be very small, and 32 % in the cavity, where large variations might be expected (though signals are lower, due to the reduction in total number density, and thus instrument precision will be poorer too). The Raman system was calibrated using H_2 -air and 70% CH_4 /30% H_2 -air flames stabilized on a 25-mm-square Hencken burner (Technologies for Research Model RT1x1) at ambient pressures, and the resulting temperatures and species mole fractions are shown in [Figures 5 and 6](#). Each calibration point is for 200 laser shots, where the values of mean and standard deviation are shown. The calibration factors for each species are shown in [Figure 7](#) with the exception of CH_4 which had a constant value of $5.28 \times 10^{20} \text{ \#}/\text{m}^3$ taken at room temperature. Sample calibration spectra are also shown in [Figure 8](#). The magnitude of cross talk between species and from OH or O_2 fluorescent interferences was determined during the calibration procedure. OH LIF was subtracted from H_2O and CH_4 Raman signals, while O_2 LIF was subtracted from H_2 , CH_4 , O_2 , and CO_2 Raman signals. Rotational Raman scattering from H_2 was subtracted from the CO_2 , O_2 , and CO lines, and a tertiary vibrational mode of CH_4 is also subtracted from O_2 . Finally, cross talk between O_2/CO_2 and CO/N_2 signals as a function of temperature was determined from the calibration data. A more detailed description of this procedure is given elsewhere [27-29]. As a result of the various experimental constraints such as having to focus close to a window, absolute accuracy of these measurements is lower than typically found in open flow configurations; however, these results still adequately capture changes in species concentration and temperature.

Since the Raman scattering measurements provide all major species and temperature, these scalar values can be plotted against mixture fraction to deduce chemistry-turbulence interaction. Mixture fraction, ξ , is a conserved scalar that is not affected by either the rate of the reaction or its progress and is only indicative of the mixing between the fuel and air streams. By normal definition, ξ is 0 in the air stream and 1 in the fuel stream. The following definition of mixture fraction, modified by Pitsch and Peters [30] based only on the presence of C and H atoms, is used:

$$\xi = \frac{Y_C + \frac{v_H}{v_C} Y_H}{Y_{C,1} + \frac{v_H}{v_C} Y_{H,1}}$$

where v_j are the stoichiometric elemental coefficients (for this fuel mixture: $v_C = 7$, $v_H = 34$), Y_i are elemental mass fractions, and the subscript 1 represents the fuel stream. The stoichiometric

mixture fraction for this fuel (with volumetric composition of $X_{\text{CH}_4} = 0.7$ and $X_{\text{H}_2} = 0.3$) is 0.0525.

3. Experimental Results

Typically, the cavity was lit (using two spark igniters located on the cavity floor) with a specific fuel flow rate (for repeatable ignition); the fuel flow rate was then changed to the desired setting, and the spectra were collected; afterwards, the fuel was shut off, and the cavity was allowed to cool (before making measurements at the next location). While no videos or photographs were taken for the current experiment, the cavity flame looked qualitatively similar to previous C_2H_4 fueled flames [31]. At 8 vertical locations (9 locations at $x = 3.5$ cm), 200 images were collected (from 200 laser shots), starting above the cavity shear layer and ending at the lowest point in the cavity accessible before the beam was clipped by the tunnel side-wall window frame. After a single vertical sweep was completed, the probe region was then moved axially from the upstream edge to the downstream edge of the cavity. The data taken along each Raman line were then divided into 7 line segments, each representing sample volumes of $0.75 \times 0.75 \times 1.5 \text{ mm}^3$. Upstream regions of the cavity suffered from considerable LIF interference, as shown in Figure 9 alongside an example with minimal interference, and as a result some fraction of the images could not be reliably reduced (converted to concentration). Therefore, to increase the available sample size at each probe location, the data from all 7 line segments were individually reduced and then bundled together to calculate mean scalar values. The resultant number of “reducible images” from this bundling is shown in Figure 10. Experimental data of mean and RMS fluctuations are shown in Figures 11-19. As can be seen from the data in Figures 11-13, at $x = 0.9$ cm there is a high concentration of CH_4 (X_{CH_4}) with little CO_2 at high temperatures, caused by the relatively fast reaction of H_2 . Furthermore, recirculation near the step in the x - z plane (see counter-rotating vortex shown in Figure 2) can effectively trap unreacted fuel, increasing residence time and creating fuel rich pockets. Therefore, it is suggested that this LIF interference is from soot precursors [e.g., polycyclic aromatic hydrocarbons (PAH)] formed from this rich region, since such a broadband LIF interference has been observed previously from PAH and soot precursors (see Figure 14.6 in ref. [13]); nonetheless, it is noted that no test was performed to confirm PAH fluorescence as being the source of interference and no soot emission has been observed in the cavity (even with ethylene fuel, regardless of fuel flow rate). The mixture fraction data in Figure 19 show rich mixtures ($\xi > 0.05$) along the floor and behind the step of the cavity, further corroborating the PAH fluorescence interference hypothesis. In addition, the mixture fraction steadily decreases along the shear layer, due to turbulent transport of O_2 into the cavity. By $x = 6$ cm on the ramp, the mixture is lean ($\xi < 0.05$) with little fuel and fluorescence interference, and almost all of spectra are reducible.

Interpretation of the RMS fluctuation data is complicated by the convolution of chemical reactions and recirculation; therefore, scatter plots will be discussed first. For the sake of analysis, the cavity combustor is divided into four regions to show the extent of mixing/chemistry throughout the combustor with two more locations, in the freestream (Location 1) and in the shear layer (Location 2) shown in Figure 20. To reduce data biasing due to the fluorescence interference, points were chosen such that at least 90% of the images were reducible. The primary recirculation pattern of the cavity is also shown in Figure 20 and

illustrates how the fuel jet (shown as the red arrow) would first pass through Locations A through D in order before either recirculating or exiting the cavity (at the ramp). Hot products can also leave the cavity *via* turbulent transport through the shear layer (e.g. Location 2). Scatter plots for Locations 1, 2, and A through D are shown in **Figures 21-26** with lines drawn for the appropriate adiabatic equilibrium- and mixing-without-reaction scalar values. Values greater than the equilibrium lines can be caused by measurement error, due to low signal levels, or to recirculation of hot gases.

Location 1, which is in the freestream where there should be negligible fluctuations, is included to demonstrate the uncertainty of the measurement. Other than a few instances (of CO₂ detection due to cross-talk with O₂), only O₂ and N₂ are observed, as expected. As a result of the low signal levels, the mean X_{O_2} is under-predicted by ~2% (i.e., $X_{O_2} = 0.19$ vs. 0.21) and both X_{N_2} and X_{O_2} RMS fluctuations are ~1.3%. Location 2 shown in **Figure 22** is included to demonstrate turbulent transport across the shear layer. Mean X_{O_2} values are roughly half that found in the main air flow over the cavity but are higher than the X_{O_2} inside the cavity, while RMS fluctuations are almost twice as large in the shear layer as in the main air flow. Temperature mean and RMS fluctuation values at Location 2 are also elevated relative to the main flow but are lower than in the cavity. Trace amounts of CH₄ and products are also seen in the shear layer as opposed to the main flow.

At Location A (see **Figure 23**), the scatter plots demonstrate that this region has intermittent partially reacted and unreacted mixtures. The CH₄ data is almost entirely along the *mixing-without-reaction* line, indicating that most of the CH₄ has not reacted at this point in the cavity, although it has started to mix, as indicated by the points below $\xi = 0.5$. Temperatures and X_{H_2O} vary from near adiabatic to unreacted values for $\xi < 0.15$, whereas for $\xi > 0.15$ there are super-equilibrium temperatures and X_{H_2O} values. CO and CO₂ values are between the *mixing-without-reaction* and equilibrium lines for lean conditions, but with super-equilibrium CO₂ values between $0.05 < \xi < 0.1$. Since little CH₄ has reacted at Location A, the high temperatures and X_{H_2O} must be from either H₂ combustion or from recirculation, and the presence of CO and CO₂ must primarily be due to recirculated products.

At Location B (see **Figure 24**), CH₄ is still largely unreacted, although more air has been entrained into the fuel jet than at Location A. CH₄ is most likely still present here in spite of the high temperatures and available oxygen, due to a ~270 μ s residence time (estimated based the ~4 cm distance between Location B and the fuel injection location and using the jet exit velocity of 150 m/s). Both the X_{O_2} and the X_{CO} profiles indicate partially reacted mixtures, while there is little CO₂ observed in this region since CO oxidation is significantly slower than the competing CH₄ breakup. Super-equilibrium values for temperature are probably due to interference and measurement error. Since there are comparable X_{CO} values at Locations A and B, it is unlikely that the disappearance of CO₂ at Location B is caused by dissociation.

At Location C (see **Figure 25**), while some of the CH₄ has yet to react, the mixture is predominantly lean and reacted or at least partially reacted. When the flow moves to Location D (see **Figure 26**), the O₂ and CO data primarily follow the *adiabatic equilibrium* lines while temperature and X_{CO_2} profiles still show partial reaction. The scatter in the CO₂ data indicates that CO oxidation occurs between Locations C and D, which is further corroborated by the CH₄ data approaching the *adiabatic equilibrium* line between these points. The X_{H_2} scatter plots, included for Locations C and D, indicate partial reaction of H₂, which was not found at the other locations. The presence of H₂ near the shear layer at Locations C and D can be explained by the *water shift* reaction :

The excess H_2 above 30% in the equilibrium curves (see [Figures 25 and 26](#)) are also due to this *water shift* reaction.

Returning to [Figures 11-19](#), fluctuations in ξ and X_{CH_4} peak near the injection location, due to intense fuel/air mixing, while fluctuations near the step (before CH_4 starts to react) are less. The profiles for CO RMS fluctuations and concentrations are similar, and in general there is less CO when X_{CH_4} is high, as expected, due to CO oxidation kinetics. X_{CO_2} fluctuations peak in regions of CO oxidation, primarily near the shear layer or in regions of recirculation near the ramp, while fluctuations lower in the cavity are most likely due to recirculation.

The RMS profiles for temperature, $X_{\text{H}_2\text{O}}$, and X_{O_2} are flatter than profiles of other scalars. Inspection of the scatter plots would indicate that the initial X_{O_2} fluctuations are due to fuel/air mixing or the consumption of O_2 in the chain-branching reaction steps, while the fluctuations further away from the injectors are due to slowly reacting CH_4 or turbulent transport of O_2 across the shear layer. Inspection of Location A data demonstrated that fluctuations in both $X_{\text{H}_2\text{O}}$ and temperature were due to either the reaction of injected H_2 or to recirculation. Additionally, the scatter plots showed that H_2O was not fully at equilibrium at Location D over the ramp (although comparisons between Locations C and D indicate that H_2O is approaching full equilibrium) due to continued formation from late burning CH_4 and from consumption due to *water shift* reactions and oxidation of CO. The “flatness” of the $X_{\text{H}_2\text{O}}$ and X_{O_2} RMS profiles is probably due to recirculation/turbulent transport and the slow reaction of CH_4 . The “flatness” of the temperature RMS profile can be explained with similar arguments. Considering that heat release primarily occurs as a result of H_2O and CO_2 formation, this flatness of the X_i profiles could be because product formation is spread out across the cavity. This may also be a consequence of the fast reaction of H_2 and relatively slow reaction of CH_4 . While this was an expected result, the use of only temperature and/or PLIF measurements would not be sufficient to prove this point. Additionally, a similar result might be expected even for a cracked jet-fuel, since ethylene (C_2H_4) would react much faster than the other components, again producing “staged” combustion. In any event, this study provides a benchmark database with a relatively simple chemistry (as compared to higher order hydrocarbons or jet fuel) in a complex geometry and flow field, which we believe will be useful for validation of advanced computational tools.

4. Conclusion

UV spontaneous Raman scattering measurements of temperature and major species concentrations (H_2 , CH_4 , CO_2 , CO, O_2 , and N_2) were recorded over a ramp close-out cavity in the Mach-2 scramjet test section of Research Cell 19 at Wright-Patterson Air Force Base. These measurements—the first of their kind—were made in spite of various challenges including low gas density, the presence of windows (near the probe region), and fluorescence interferences typical of practical combustors and fuels. While the presence of broadband fluorescence interference exacerbated the signal quality and increased measurement uncertainty, the data were of sufficient quality that significant conclusions could be made regarding combustion within the pilot of a scramjet combustor.

The cavity flow field was directly fueled from the ramp using a fuel composed of 70% CH_4 and 30% H_2 (by volume). Results showed that H_2 fuel quickly reacted while the CH_4 fuel reacted slowly. Indeed, CH_4 was largely unreacted by the time it reached the leading edge of the cavity, forming a fuel-rich region along the floor and behind the step at high temperature (due to

the fast reaction of H_2). This region of hot, unreacted CH_4 may have resulted in production of polycyclic aromatic hydrocarbons (PAH), thus creating the broadband interference observed in this region.

Measurements of mixture fraction indicated that the cavity was rich overall; however turbulent transport of O_2 across the shear layer eventually resulted in lean mixtures over the ramp. The path of the injected fuel was traced out through the cavity using scatter plots, and CH_4 was mainly unreacted near the injectors and behind the step, partially reacted by the midpoint of the cavity below the shear layer, and reacted near the ramp where the products will either exit the cavity or recirculate. Comparisons between CO and CO_2 concentration profiles showed that CO began to oxidize after the CH_4 concentrations decreased near the midpoint of the cavity below the shear layer and that CO was nearly gone by the ramp, although there was still scatter in the CO_2 concentration. While the H_2 fuel quickly reacted near the ramp injectors, H_2 concentrations were observed where CO began to oxidize, probably due to the *water shift* reaction. Data taken in the shear layer demonstrated turbulent transport across the shear layer of O_2 into the cavity and hot products into the main flow of tunnel. Fluctuations in measured temperature and O_2 , and H_2O concentration were fairly constant throughout the cavity, primarily due to the slow reaction of CH_4 and to a combination of recirculation of hot products and turbulent transport of O_2 across the shear layer.

Even though the H_2 fuel component quickly reacted, providing the high temperature and radicals to sustain the reaction, the slow reaction of CH_4 delayed the formation of both CO and CO_2 . Additionally, these results show the importance of measuring all major species when multi-component fuels are used, in order to properly determine the combustion behavior and progress, even in the relatively simple fuel mixture used in the current experiment. Finally, this study provides a benchmark database with a relatively simple chemistry in a complex geometry and flow field that can be used for validation of advanced computational models and simulations.

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Figure 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 ($x = 0, y = 0, z = 0$)

Figure 2: Close-up of the fuel (red stars) injectors from the side (top) and from above at an angle (bottom). The 11 fuel injectors are spaced 12.7 mm apart with an exit diameter of 1.98 mm supplying a 70% CH_4 /30% H_2 fuel blend. The recirculation zones and flow patterns are indicated in the top figure.

Figure 3: Schematic of the UV Raman experimental system (left) with side view of collection system (right).

Figure 4: Sample mean wall pressures and the standard deviation of the 1-Hz measurement was generally $<1\%$. Insert shows the pressure port locations (solid triangles) with respect to the cavity. Flow pattern sketched following Figure 5b in [20].

Figure 5: Calibration plots of Raman data over a Hencken burner using an H_2 -air flame at ambient (laboratory) pressure. The points are the mean values and the bars represent one standard deviation. Solid lines represent adiabatic equilibrium values.

Figure 6: Calibration plots of Raman data over a Hencken burner using a 70% CH_4 /30% H_2 -air flame at ambient (laboratory) pressure. The points are the mean values and the bars represent one standard deviation from the mean. Solid lines represent adiabatic equilibrium values.

Figure 7: Calibration factors, $C(T)$, vs. temperature obtained from the Hencken burner. The $C(T)$ for CH_4 measured at room temperature and assumed to be invariant with temperature.

Figure 8: Raw, single-shot line spectral images of calibration data of 70% CH_4 /30% H_2 fuel mixture at $\phi = 1$ (left) and $\phi = 1.6$ (right).

Figure 9: Raman single-shot spectra taken inside the combustor showing a reducible image (left), and an irreducible image (right) due to broadband interference during combustion both taken at $x = 0.9$ cm and $y = 0.9$ cm where the wall pressure is 37 kPa. The maximum value of the right image is $\sim 20\%$ more than the maximum of the left image.

Figure 10: Number of reducible images. The insert in the upper left represent the maximum value of the figure.

Figure 11: Experimental mean (black) and RMS fluctuation (red) temperature data. The insert in the upper left represent the maximum value of the figure.

Figure 12: Experimental mean (black) and RMS fluctuation (red) CH_4 data. The insert in the upper left represent the maximum value of the figure.

Figure 13: Experimental mean (black) and RMS fluctuation (red) CO_2 data. The insert in the upper left represent the maximum value of the figure.

Figure 14: Experimental mean (black) and RMS fluctuation (red) CO data. The insert in the upper left represent the maximum value of the figure.

Figure 15: Experimental mean (black) and RMS fluctuation (red) H_2O data. The insert in the upper left represent the maximum value of the figure.

Figure 16: Experimental mean (black) and RMS fluctuation (red) O_2 data. The insert in the upper left represent the maximum value of the figure.

Figure 17: Experimental mean (black) and RMS fluctuation (red) H_2 data. The insert in the upper left represent the maximum value of the figure.

Figure 18: Experimental mean (black) and RMS fluctuation (red) N_2 data. The insert in the upper left represent the maximum value of the figure.

Figure 19: Experimental mean (black) and RMS fluctuation (red) mixture fraction data. The stoichiometric mixture fraction, ξ_{st} , is 0.0525. The insert in the upper left represent the maximum value of the figure.

Figure 20: Scatter plot locations with arrows showing fuel injection (red) and the recirculation pattern (black). Location 1 is in the freestream, Location 2 is in the shear layer, and Location A through D are in the cavity.

Figure 21: Scatter plots for Location 1 ($x = 3.5$ cm, $y = 1$ cm) with lines drawn for adiabatic equilibrium (solid) and mixing without reaction (dashed).

Figure 22: Scatter plots for Location 2 ($x = 3.5$ cm, $y = 0.2$ cm) with lines drawn for adiabatic equilibrium (solid) and mixing without reaction (dashed).

Figure 23: Scatter plots for Location A ($x = 3.5$ cm, $y = -1.1$ cm) with lines drawn for adiabatic equilibrium (solid) and mixing without reaction (dashed).

Figure 24: Scatter plots for Location B ($x = 0.9$ cm, $y = -1.1$ cm) with lines drawn for adiabatic equilibrium (solid) and mixing without reaction (dashed).

Figure 25: Scatter plots for Location C ($x = 3.5$ cm, $y = -0.1$ cm) with lines drawn for adiabatic equilibrium (solid) and mixing without reaction (dashed).

Figure 26: Scatter plots for Location D ($x = 6$ cm, $y = -0.3$ cm) with lines drawn for adiabatic equilibrium (solid) and mixing without reaction (dashed).