Tunable diode laser absorption spectroscopy (TDLAS) has been used to make path-integrated temperature measurements in a gaseous oxygen / gaseous hydrogen uni-element rocket chamber with hot background flow. Four mixture conditions were studied at a nominal chamber pressure of 100 psia. Near infrared diode lasers were utilized to target rovibrational transitions of water vapor combustion product. Both direct absorption spectroscopy and wavelength modulation spectroscopy with second harmonic normalized by first harmonic (1f-normalized WMS-2f) techniques were applied, with the harmonic detection technique found to yield the best results. Illustrative examples of time-resolved measurements of temperature in the rocket chamber are presented.

Nomenclature

\[ a = \text{laser scan depth} \]
\[ A = \text{integrated absorption} \]
\[ D = \text{diameter} \]
\[ DFB = \text{distributed feedback} \]
\[ f = \text{frequency} \]
\[ E'' = \text{lower state energy} \]
\[ FM = \text{frequency modulation} \]
\[ FWHM = \text{full-width-at-half-maximum} \]
\[ H = \text{Fourier harmonic} \]
\[ i_0, i_2 = \text{linear and non-linear intensity modulation amplitudes} \]
\[ I = \text{transmitted intensity of laser radiation} \]
\[ I_0 = \text{incident intensity of laser radiation} \]
\[ IM = \text{intensity modulation} \]
\[ L = \text{pathlength} \]
\[ MC = \text{main chamber} \]
\[ n = \text{coefficient of temperature dependence} \]
\[ N = \text{total number of species} \]
\[ O/F = \text{mixture ratio, oxidizer-to-fuel, by mass} \]
\[ P = \text{pressure} \]
\[ PB = \text{preburner} \]
\[ P_3 = \text{pressure upstream of injector} \]
\[ Q = \text{partition function} \]
\[ R_{1f} = \text{first harmonic signal} \]
\[ S = \text{linestrength} \]
\[ S_{2f} = \text{second harmonic signal} \]
\[ t = \text{time} \]
\[ T = \text{temperature} \]
\[ \text{TDLAS} = \text{tunable diode laser absorption spectroscopy} \]
\[ x = \text{position} \]
\[ X = \text{mole fraction} \]
\[ V = \text{velocity} \]
\[ \gamma = \text{broadening coefficient} \]
\[ \psi_1, \psi_2 = \text{linear and nonlinear IM/FM phase shift} \]
\[ \phi = \text{lineshape function} \]
\[ \tau = \text{transmission coefficient} \]
\[ \omega_m = \text{angular frequency} \]
\[ \nu = \text{wavenumber} \]
\[ \Delta \nu_C = \text{pressure-broadened half-width} \]

Subscripts

\[ abs = \text{absorbing molecule} \]
\[ j = \text{species number} \]
\[ ref = \text{reference condition} \]

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I. Introduction

Over the last four decades, considerable attention has been given to the study of combustion inside high pressure rocket combustors. These studies have focused on such aspects as optimization of fuel injector and combustion chamber designs, propellant mixing and combustion instability to produce more reliable and efficient liquid propellant rocket engines. Currently, there are significant efforts underway to develop robust computational fluid dynamics models that can be used to simulate combustion in a rocket chamber, thereby allowing for a more mature engine design before the overall system is assembled and tested. The objective is for these CFD codes to save considerable amount of time and money in designing new rocket engines, for example by establishing performance and safe operating conditions without the need for expensive full scale testing.

A small number of research test facilities around the globe operate subscale rocket motors to study the complex combustion process inside a rocket chamber. By utilizing a single or small number of injector elements that flow propellants at realistic flow conditions, these subscale rocket combustion chambers provide a good comparison with full-scale, multi-element injector chambers such as in the Space Shuttle Main Engine or the J-2X engine. Because of the relatively inexpensive cost of testing sub-scale rocket motors (when compared to full-size rocket engines), these testbeds are valuable for providing quantitative and qualitative information about the flowfield and combustion process for various injector designs, and data from these tests are used extensively by CFD modelers when attempting to benchmark and validate their model codes.

Because of the desire to have in-situ combustion measurements, it is advantageous to utilize optical diagnostics. Numerous non-intrusive laser diagnostic methods have been applied successfully by combustion researchers over the past few decades to study combustion processes, although application of these methods to practical combustion problems has been more limited. Rockets present special challenges for optical diagnostics, primarily due to the need for optical access in high pressure, high temperature chambers with harsh combustion environments.

The most useful measurements in a rocket combustor are typically velocity, temperature and major species concentration profiles of the flowfield. At the Cryogenic Combustion Laboratory (CCL) at The Pennsylvania State University, a number of laser diagnostic methods have been applied successfully to make these quantitative measurements with optically accessible rocket chambers. Diagnostic methods that have been demonstrated successfully for gaseous propellants include Laser Doppler Velocimetry (LDV) for velocity field measurements, and Raman Spectroscopy for major species concentration field and temperature. In addition to these methods, Laser-Induced Fluorescence (LIF) from OH-radicals and laser light scattering studies using seeded combustion flow have been performed to obtain quantitative information on flame shape and propellant mixing. Other non-optical measurements that have been conducted include measurements of chamber temperature profiles and chamber wall heat flux. Using these various methods, a series of uni-element rocket injector studies have been previously completed to provide benchmark quality data needed to validate CFD models. These studies have demonstrated that quantitative data can be obtained for practical rocket combustion flowfields.

The principle limitation for these measurements, however, is that they are all either time-averaged or instantaneous (single-shot) measurements. This is of particular significance because of the highly transient and turbulent nature of the combustion flowfield in a rocket chamber. Using these described methods, it has not been possible to continuously “freeze” the flow in the chamber. To better understand the complex physics involved in these processes, it is necessary to make high-speed, time-resolved measurements (1000 Hz and higher) inside the chamber.

A. Cryogenic Combustion Laboratory (CCL)

The CCL is a university facility where researchers conduct work on representative rocket engine flowfields. The laboratory is designed based on a similar test cell at NASA Lewis Research Center (now the NASA Glenn Research Center at Lewis Field). The CCL, a remotely controlled laboratory, features a control room, diagnostic room and the test cell. The test cell, where the combustion experiment is housed, is isolated from the control and diagnostic rooms with reinforced concrete walls. The diagnostic room located adjacent to the test cell is utilized for situating all the laser-based diagnostics. Optical ports between the diagnostics room and the test cell provide access into the test cell. The control room houses the computer control system that is used for timing the rocket firing.
The propellant flowrate capabilities of the laboratory are listed in Table 1.

### B. Rocket Assembly

The rocket chamber assembly developed for these experiments, illustrated in Figure 1, has a single gaseous oxygen (GO\textsubscript{2}) / gaseous hydrogen (GH\textsubscript{2}) shear-coaxial injector element, surrounded by a multi-hole injector plate for hot co-flow of combustion products from a GH\textsubscript{2}/GO\textsubscript{2}/gaseous helium (GHe) preburner (PB) system. The main chamber (MC) of the rocket has a 1.0 in. square cross-section. The main injector is a shear-coaxial injector with a GO\textsubscript{2} post inner diameter of 0.207 in., a GH\textsubscript{2} annulus inner diameter of 0.247 in., and GH\textsubscript{2} annulus outer diameter of 0.295 in. (GO\textsubscript{2} post thickness is 0.020 in.) The background flow from the preburner is injected into the chamber by an injector plate with 78 holes, each with 0.047 in. diameter, surrounding the main fuel and oxidizer injector post (as illustrated in Figure 1). In the preburner an impinging injector is used. This injector has a central 0.065 in. diameter GO\textsubscript{2} hole surrounded by six angled 0.031 in. diameter holes for GH\textsubscript{2}. GHe is injected downstream of the main preburner injector through four radial holes (each with 0.170 in. diameter).

The propellants in the main chamber and preburner are ignited using two identical GO\textsubscript{2}/GH\textsubscript{2} torch igniters. GO\textsubscript{2} and GH\textsubscript{2} are injected off-axis into the igniter and are ignited using a spark plug driven by an oil furnace ignition transformer. Ignition is detected by a pressure rise in the igniter combustion chamber. The pressure rise in the igniter is checked before propellants are introduced to the main chamber and preburner. The hot gases from the igniters flow into the integrated rocket assembly and ignite the propellant flows in the preburner and main chamber.

The rocket chamber is a heat sink design made of oxygen-free high conductivity (OFHC) copper, and is modular so that it can be easily configured to accommodate changes in chamber length or hardware configurations, such as sensor placement or injector design. The chamber sections are held together with a hydraulic jack that allows for easy assembly and arrangement of the various sections. The design allows for operational pressures of up to 1000 psia, and a water cooled nozzle allows for GO\textsubscript{2}/GH\textsubscript{2} operation at near stoichiometric conditions. The design of the water cooled nozzle allows for different diameter nozzles to be interchanged, thus providing the capability of changing the main chamber pressure for a given total propellant mass flow rate. The chamber was designed to

#### Table 1. Flowrate capabilities of CCL.

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Maximum Flowrate (lbm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaseous Oxygen (GO\textsubscript{2})</td>
<td>1</td>
</tr>
<tr>
<td>Gaseous Hydrogen (GH\textsubscript{2})</td>
<td>0.25</td>
</tr>
<tr>
<td>Gaseous Hydrogen (GCH\textsubscript{4})</td>
<td>0.5</td>
</tr>
<tr>
<td>Liquid Oxygen (LOX)</td>
<td>1</td>
</tr>
<tr>
<td>Liquid Hydrocarbon</td>
<td>0.5</td>
</tr>
<tr>
<td>Air</td>
<td>5</td>
</tr>
</tbody>
</table>

![Figure 1. Schematic of rocket chamber assembly with preburner. The large windows are replaced with small optical ports for diode laser measurements.](image)
accommodate large windows for optical access on three sides of the combustion chamber, allowing for multiple optical diagnostics to be employed simultaneously. For the experiments reported here, smaller optical ports were installed in two of the window mounts with thin 2°-wedged sapphire windows to facilitate placement of the transmission and collection optics within close proximity to the combustion zone.

A rocket design with background co-flow was chosen after discussions with rocket engine combustion modelers. This background flow is desirable because it eliminates the recirculation zone near the injector face that is typical in unicomponent rocket chambers and has been computationally problematic for many modelers. Use of a background flow of combustion products at approximately 1400 °R also eases the stress that would otherwise be placed on the chamber windows from the much hotter main combustion products, thus eliminating the need for active cooling of the windows.

Using a square chamber allows for easier placement of the flat chamber windows flush with the chamber walls, thus avoiding a flow-disrupting cavity that would occur by placing a flat window into a circular cross-section chamber. While contoured windows in a circular cross-section chamber would achieve this same result, such windows would present additional challenges for optical diagnostics. By rearranging the movable chamber sections, optical access along the entire length of the chamber is possible, from the injector face to the start of a nozzle transition section. This 1-inch long transition precedes the conical nozzle, and provides a smooth transition between the square-cross section of the chamber and the circular cross-section of the nozzle.

Bar heaters were attached to the outside of the chamber and the chamber was preheated to approximately 700 °R prior to all tests. This was done to prevent water, which is created inside the chamber through the combustion process, from condensing on the cool window surfaces and obscuring the laser signals. Additionally, the torch igniters are purged briefly following ignition to remove any condensed water build-up that could interfere with the diode laser measurement in the main chamber.

C. Flow Conditions
1. Preburner-Only Configuration

High pressure, high temperature calibration data is needed for the absorption spectroscopy system, which is detailed in the next section (additional details provided in Ref. 11). An alternate configuration for the rocket assembly was utilized to gather calibration data for the absorption spectroscopy measurements and to validate the TDLAS system. In this configuration, the main rocket injector was blocked off and propellants were fed only to the preburner. For this configuration, one of the three quartz windows of the rocket chamber was replaced with a copper blank, instrumented with three type-K thermocouples. These thermocouples were arranged to form a rake across the centerline of the combustion chamber, approximately 6-in. downstream of injector face (slightly downstream of the laser path). Thus, with relatively minor modifications to the experimental setup, it was possible to establish in the optically-accessible chamber a uniform (±50 °R) high temperature flow from which to make calibration measurements.

For pressures above 50 psia, flow rates to the preburner were scaled from the 100 psia baseline case with the nozzle diameter fixed. For pressures below 50 psia, the flow rates were set to match the 50 psia case, and the nozzle size was increased to give the appropriate chamber pressure. A test series without GHe was conducted, with excess GHe plumbed into the preburner to produce a mixture ratio of 0.72, providing a data set without helium-broadening effects on the spectral linewidths of the H2O absorption features.

2. Full Rocket Configuration

For the full configuration rocket tests, two different mixture ratios (O/F, on a mass basis) of 6.0 and 4.25 were targeted for the main rocket injector. Hot background flow was provided from the preburner. For each oxidizer-fuel mixture ratio, two variants were studied: undiluted oxidizer and fuel flows, and dilution with GHe introduced into both the GO2 and GH2 main injector flows. GHe was introduced for these off-nominal cases to force a reduction in the flame temperature in main chamber to a level corresponding to maximum sensitivity of the TDLAS system. These cases aided in the validation of the system by providing a range of mixture temperatures and compositions to apply the sensor system.

The preburner for the background flow (GO2+GH2+GHe) was also operated fuel-rich at a target mixture ratio of 2.1, such that the volumetric flowrate of molecular hydrogen in the background flow matched that of the main rocket combustion products. All rocket experiments were conducted utilizing the same nozzle (throat diameter 0.317 in). A single chamber pressure of 115 psia was targeted for all tests. Actual flow conditions achieved for these tests are presented in Table 2.
The timing of valve openings and closings is controlled by Program Logic Control. The sequence is divided into four zones, namely pre-firing (zone 1), firing (zone 2), post-firing (zone 3), and abort (zone 4) periods. The time duration of each zone is variable, and is set according to each test. For the purposes of this paper, all times shown are referenced to the start of zone 2. The duration of zone 2 for the current study was 10 s.

Table 2. Summary of flow conditions achieved for four cases tested.

<table>
<thead>
<tr>
<th>Condition</th>
<th>O/F 6.0 Diluted</th>
<th>O/F 6.0 Undiluted</th>
<th>O/F 4.25 Diluted</th>
<th>O/F 4.25 Undiluted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Number</td>
<td>120910_0010</td>
<td>120910_0013</td>
<td>121410_0015</td>
<td>121410_0020</td>
</tr>
</tbody>
</table>

**Overall:**
- Main Chamber Pressure (psia) 115.7, 109.4, 116.1, 112.6
- Preburner Pressure (psia) 118.9, 113.6, 119.3, 117.8

**Main Chamber:**
- Mass Flowrate GO₂ (lbm/s) 0.0137, 0.0168, 0.0124, 0.0147
- Mass Flowrate GHe into GO₂ (lbm/s) 0.0035, - , 0.0036, -
- MW_mix 13.2, 32.0, 12.5, 32.0
- Density at Injector Exit (lbm/ft³) 0.28, 0.63, 0.27, 0.67
- Temperature of Flow (R) 509, 514, 502, 505
- Velocity of Flow (ft/s) 265, 114, 254, 95
- Reynolds Number* of Oxidizer Flow, ReD 91547, 84531, 86212, 73977

**Injector Characteristics:**
- Velocity Ratio (Annulus Flow/Post Flow) 4.0, 4.2, 4.6, 5.9
- Mass Flow Ratio (Post Flow/Annulus Flow) 1.6, 6.1, 1.4, 4.3
- Momentum Ratio (Annulus Flow/Post Flow) 2.6, 0.7, 3.4, 1.4
- Momentum Flux Ratio (Annulus Flow/Post Flow) 4.3, 1.1, 5.6, 2.3

**Background Flow (Preburner):**
- Mass Flowrate (lbm/s) 0.0176, 0.0217, 0.0177, 0.0215
- Density at Injector Exit (lbm/ft³) 0.035, 0.033, 0.036, 0.034
- Temperature of Flow (R) 1400, 1400, 1400, 1400
- Velocity of Flow (ft/s) 77, 100, 77, 97
- O/F 2.1, 2.1, 2.1, 2.1

**Overall:**
- Density of Overall Flow in Main Chamber (lbm/ft³) 0.022, 0.019, 0.023, 0.020
- Velocity of Overall Flow in Main Chamber (ft/s) 300, 321, 284, 288
- Mach # of Overall Flow in Main Chamber 0.050, 0.053, 0.049, 0.048
- Reynolds Number† of Overall Flow in Main Chamber 13566, 10076, 14851, 10957

*Based on GO₂ post-diameter
†Based on chamber hydraulic diameter.
III. Absorption Spectroscopy

A. Theory
In absorption spectroscopy, a laser is tuned to a wavelength coincident with an electronic, vibrational or rotational transition of the molecule of interest, in this case water. By making simultaneous measurements at two wavelengths with separate lasers, the temperature of the water vapor can be determined.

The basis of absorption spectroscopy is the Beer-Lambert law,
\[
\ln \left( \frac{I}{I_0} \right) = -\int_0^L PX_{abs}(x)S(T(x))\phi dx,
\]
where \( I \) is the intensity of the transmitted light, \( I_0 \) is the intensity of the incident light, \( P \) is the pressure, \( X_{abs}(x) \) is the mole fraction of the absorbing species, which is a function of \( x \), \( S(T(x)) \) is the linestrength which is a function of the temperature, \( \phi \) is the lineshape function, and \( x \) is the coordinate along the laser beam pathlength. The lineshape function, \( \phi \), can be represented by a Voigt profile,\(^{12-16}\) which is a convolution of the Gaussian profile (for Doppler broadening) and the Lorentz profile (for collisional broadening). The Voigt profile is a function of the independent broadening parameters of the transition of interest.

1. Direct Absorption Spectroscopy
In direct absorption spectroscopy, a laser is typically scanned through a wavelength range corresponding to an absorption feature. It is often possible to resolve the entire lineshape of the transition feature being targeted. This is achieved by finely tuning the laser drive current and \( I \) or temperature to alter the wavelength of the probing laser. By measuring the lineshape, the linestrength and broadening coefficients of the transition can be inferred. In this method, the baseline intensity needed for the Beer-Lambert relationship is determined by fitting the portion of scan that is unaffected by the absorption feature. Because fitting the entire lineshape includes any line broadening effects, the ratio of linestrengths of two or more lines become a function of temperature only, thus allowing for a very simple and accurate way to measure temperature in a gas sample. This method is referred to as “two-line thermometry.” Since two transition lines are measured at the same instant and have the same pressure, mole fraction and pathlength, their ratio becomes,
\[
R = \frac{A_1}{A_2} = \frac{\int PL\phi_{11}S_1(T)dv}{\int PL\phi_{22}S_2(T)dv} = \frac{S_1(T)}{S_2(T)},
\]
where \( A \) is the integrated absorption. The linestrength, \( S(T) \), of a transition can be written as a function of a known linestrength at some reference temperature as follows,\(^{17}\)
\[
S(T) = S(T_{ref}) \frac{Q(T_{ref})}{Q(T)} \exp\left(-c_2E^*/T\right) \exp\left(-c_2E^*/T_{ref}\right) \left[1 - \exp\left(-c_2v/T\right)\right]\left[1 - \exp\left(-c_2v/T_{ref}\right)\right],
\]
where \( c_2 \) is the second radiation constant, \( E^* \) is the lower state energy, and \( v \) is the linecenter wavenumber. The values of the partition function, \( Q \), are calculated using the values tabulated by Vidler and Tennyson.\(^{18}\)

By measuring the lineshape, \( \phi \), it is also possible to distinguish the effects of nearby or overlapping transitions on the measured absorption. Unfortunately, the time resolution of a sensor utilizing scanned wavelength absorption is limited to the rate at which the laser can be tuned over the absorption feature. The wider the absorption feature (for example at higher pressures), the greater the tuning depth required and the lower the repetition rate, or sensor bandwidth, will be. At present, tunable diode laser sensors have been developed that operate from 1 kHz up to 50 kHz.\(^{19-28}\)

The time resolution of scanned wavelength absorption can be improved significantly if one uses the peak height only of the absorption feature to determine the temperature. In doing so, the time resolution of the measurement is limited only by the responsiveness of the photodetector and data acquisition system. Unfortunately, peak height is a function not only of temperature, but also partial pressure of the absorbing species and all perturbing species through the feature lineshape,
\[
R = \frac{P \cdot X_{abs} \cdot L \cdot S_1(T) \cdot \phi_1(v_0, T, P, X)}{P \cdot X_{abs} \cdot L \cdot S_2(T) \cdot \phi_2(v_0, T, P, X)} = \frac{S_1(T) \cdot \phi_1(v_0, T, P, X)}{S_2(T) \cdot \phi_2(v_0, T, P, X)}.
\]
The lineshape functions, $\phi_1$ and $\phi_2$, in Eq. 4 are not measured and must be determined separately. This can be accomplished through calibration experiments to carefully determine the temperature and collisional broadening dependency of the lineshape for the particular transition being targeted. With this information, the temperature can be inferred from the measured ratio of peak absorption for two or more different temperature-dependant transitions, along with the lineshape information.

2. Wavelength Modulation Spectroscopy (WMS)

A more advanced technique for absorption spectroscopy involves harmonic detection using a modulated laser signal. Here, an external modulation is superimposed over the laser drive-current, which itself can be either scanned or fixed. These methods have been extensively developed\(^{19,22,28-38}\) for sensing of trace-species, and can greatly reduce the noise encountered in direct absorption measurements. Detection of the second harmonic ($2f$) is typical (detection at twice the modulation frequency).\(^{32,39}\) Second harmonic detection produces a zero-baseline signal, eliminating the need to accurately measure a baseline single. Because of the modulation frequency, typically in the kilohertz frequency domain, low frequency noise can be eliminated with wavelength modulation spectroscopy. Modulation is typically performed with small modulation depths, suitable for narrow, isolated absorption features, although recent advances have shown that WMS can be suitable for high pressure applications as well.\(^{30,40-44}\)

If the injection current driving the diode laser is sinusoidal with frequency (Hz), the instantaneous laser frequency modulation (FM) can be described as,

$$\nu(t) = \tilde{\nu} + a \cos(\omega_m t),$$

where $\tilde{\nu}$ is the center laser frequency (cm\(^{-1}\)), $a$ is the modulation depth (cm\(^{-1}\)), and $\omega_m$ is the angular frequency ($= 2\pi \times$ modulation frequency). The laser intensity modulation (IM), can be represented as,

$$I_0(t) = \overline{I}_0 + i_0 \cos(\omega_m t + \psi_1) + i_2 \cos (\omega_m t + \psi_2),$$

where $I_0(t)$ is the instantaneous laser frequency, $\overline{I}_0$ is the average laser intensity at $\tilde{\nu}$, $i_0$ and $i_2$ are the linear and nonlinear IM amplitudes respectively (normalized by $\overline{I}_0$), and $\psi_1$ and $\psi_2$ are the linear and nonlinear FM/IM phase shift values respectively.

The transmission coefficient is represented as,

$$\tau(\nu) = \tau(\tilde{\nu} + a \cos(\omega_m t)), $$

which is a periodic even function in $\omega_m t$. Therefore, the transmission coefficient can expanded by a Fourier cosine series, such that,

$$\tau(\tilde{\nu} + a \cos(\omega_m t)) = \sum_{k=0}^{\infty} H_k(\tilde{\nu}, a) \cos(k \omega_m t),$$

where $H_k$ are the Fourier harmonics of $k^{th}$ order. These harmonics are given as

$$H_0(\tilde{\nu}, a) = \frac{1}{2\pi} \int_{-\pi}^{+\pi} \tau(\tilde{\nu} + a \cos \theta) d\theta,$$

$$H_k(\tilde{\nu}, a) = \frac{1}{\pi} \int_{-\pi}^{+\pi} \tau(\tilde{\nu} + a \cos \theta) \cos k \theta d\theta,$$

where $k = \omega_m t$.

As can be seen from these equations, the harmonics are a function of the spectral lineshape function, $\phi$, and modulation depth, $a$. Note that the modulation depth is a function of the diode laser and modulation settings. Therefore, details of the experiment must be included in the model to predict second harmonic signals.

The absolute magnitude of the absorption $2f$ signal, $S_{2f}$, can be shown to be:

$$S_{2f} = \sqrt{X^2_{2f} + Y^2_{2f}},$$

$$= \frac{G \overline{I}_0}{2} \left\{ \left[ H_2 + \frac{i_0}{2} (H_1 + H_3) \cos \psi_1 + i_2 \left( H_0 + \frac{H_4}{2} \right) \cos \psi_2 \right] ^2 + \left[ \frac{i_0}{2} (H_1 - H_3) \sin \psi_1 + i_2 \left( H_0 - \frac{H_4}{2} \right) \sin \psi_2 \right] ^2 \right\} ^{1/2} \text{,}$$

where $G$ is gain parameter of the detection system.
For high pressure applications, the broadened absorption features have large FWHMs, requiring large amplitude modulation to resolve the 2f signal. This requires that the nonlinear effects of the diode lasers must be taken into account for WMS-2f with large amplitude modulation.\(^{44,45}\) The commonly used assumptions that \(i_2 = 0\) and the FM/AM phase shift, \(\psi = \pi\), no longer hold. The parameters \(i_0, i_2, \psi_1,\) and \(\psi_2\) of each diode laser need to be determined for the specific modulation depth and frequency used. Ref. \(^{44}\) reports a methodology for determining these parameters by evaluating the diode laser properties under zero absorption conditions.

Normalization of the 2f component of a signal by the 1f component (1f-normalized WMS-2f) of the same signal has been reported as a way to reduce the need to fully characterize the lasers when utilizing large amplitude modulation. This is possible because many of the laser parameters have the same effect on the 1f and 2f signals, and therefore the effects can be eliminated with a ratio of the components. This method has also been reported to eliminate the need to calibrate the system against a known gas sample. However, the remaining experimental parameters which are not eliminated from the equations through normalization must still be considered as part of the model.

The absolute magnitude of the absorption 1f signal, \(R_{1f}\), can be shown to be:

\[
R_{1f} = \sqrt{x_{1f}^2 + y_{1f}^2} = \frac{G_{1f}}{2} \left\{ \left[ H_1 + i_0 \left( H_0 + \frac{H_2}{2} \cos \psi_1 + \frac{i_2}{2} (H_1 + H_2) \cos \psi_2 \right) \right]^2 + \left[ i_0 \left( H_0 - \frac{H_2}{2} \sin \psi_1 + \frac{i_2}{2} (H_1 - H_3) \sin \psi_2 \right) \right]^2 \right\}^{1/2}.
\]

(12)

When large amplitude modulation is used, it is necessary to account for the background signal that is present even when there is no absorption signal. When there is no absorption, \(H_0 = 1\) and \(H_2 = 0\). This is known as the non-absorption background signal, or residual amplitude modulation. This becomes important for large amplitude modulation, since \(i_2 \neq 0\), and must be accounted for in the model.

With respect to the measurements, the zero-absorption background signals are accounted for by sampling the laser signals with no absorption present, and then vector-subtracting to give a final 2f/1f ratio of.\(^{43}\)

\[
\frac{S_{2f}}{R_{1f}} = \sqrt{\left( \frac{x_{2f}}{R_{1f}} - \frac{x_{0f}}{R_{0f}} \right)^2 + \left( \frac{y_{2f}}{R_{1f}} - \frac{y_{0f}}{R_{0f}} \right)^2}.
\]

(13)

An important advantage of this method is that the 1f component of the signal can be used to track transmission losses resulting from scattering, beam steering, misalignments, and/or window fouling. The 1f signal can then be used to correct the 2f component of the signal. Using direct absorption spectroscopy, the only way to correct the signal for transmission losses is to normalize by a non-absorbing reference laser. However, this reference laser is typically at a wavelength different than the wavelength of the probing laser(s). Therefore, the laser beams will not have identical transmission paths through the test medium when subjected to beam steering, and thus error is introduced into the correction. By normalizing with the 1f-component of the same laser signal, this problem is eliminated. It has been demonstrated that the 1f-normalized WMS-2f signal remains unchanged with as little as 3-4% of the original signal collected.\(^{45}\) Additionally, it has been shown that a DC offset on the absorption signal (such as due to emission or broadband absorption), has no effect of the 1f-normalized WMS-2f signal.\(^{45}\)

Finally, the temperature is determined by comparing the 2f/1f signals for two different transition lines. The ratio of 1f-normalized WMS-2f signals from two transitions lines is defined as,

\[
\text{Ratio} = \frac{\left[ \frac{S_{2f}}{R_{1f}} \right]_1}{\left[ \frac{S_{2f}}{R_{1f}} \right]_2}.
\]

(14)

Comparison of the WMS model with the experimental results is used to yield the temperature.

**B. Line-Broadening**

Absorption spectroscopy has received a great deal of attention since the advent of tunable diode lasers, particularly diode lasers in the near infrared region of the spectra.\(^{19,22,28,36,46}\) Most studies have been performed at atmospheric pressure conditions or at pressures of a few atmospheres, which is much lower than the pressures inside typical rocket chambers. A major challenge for application of absorption spectroscopy to high pressure rocket chambers is pressure broadening, due to molecular collisions, of the spectral lineshape. The line broadening effect can result in overlapping of adjacent molecular transitions, which makes the analysis of quantitative species...
concentration more challenging. At high pressures, it also becomes difficult to determine the baseline signal needed for direct absorption spectroscopy, since the entire width of the scan is impacted by the absorption feature.

The lineshape function, \( \phi \), is a function of the pressure-broadened half-width parameter, which is given empirically as,

\[
\Delta \nu_c = \left( \frac{T_{\text{ref}}}{T} \right)^n P \sum_{j} \gamma_j \left( P_{\text{ref}}, T_{\text{ref}} \right) \cdot X_j
\]

where \( P \) [atm.] is total pressure, \( T \) is temperature, \( \gamma_j \) is the collisional broadening coefficient of species \( j \), \( X_j \) is the mole fraction of species \( j \), \( N \) is the total number of species present in the medium and \( P_{\text{ref}} \) and \( T_{\text{ref}} \) are the reference pressure and temperature, respectively, and \( n \) is the temperature-dependency coefficient. The broadening of a transition line results from collisions of the target species with like-molecules (“self-broadening”), as well as molecules from all other species present (“foreign-gas broadening”), and is temperature-dependent.

In general, it is most desirable to have an isolated transition with nearby molecular transitions well spaced from the selected transition. It is well known that as pressure is increased, meeting this desired attribute is not always possible. To address this problem, a calibration procedure to directly measure the lineshape as a function of pressures and temperatures is required.

C. System Details

The absorption system (Figure 2) utilizes continuous wave distributed feedback (DFB) diode lasers. The lasers are fiber-optically coupled with a maximum power output of 10 mW. The narrow spectral linewidth lasers for targeting the \( \text{H}_2\text{O} \) transitions were selected with output wavelengths of 1343.3 nm and 1388.1 nm. A 1310 nm output wavelength, which corresponds to a non-absorbing region of the \( \text{H}_2\text{O} \) spectrum, is used to provide the reference signal \( I_0 \). The signal from this reference laser is sampled simultaneously with the other two \( \text{H}_2\text{O} \) lasers and provides a real-time non-resonant absorption value to track transmission changes of the system.

Each DFB laser is fiber-optically coupled to a single mode fiber, and all of the laser signals are multiplexed into one single mode optical fiber. 10\% of the signal is split and sent through an etalon, which is used to track the scan depth of the laser, or alternatively to a wavemeter to monitor the absolute wavelength of the signal. The remaining multiplexed light from the single mode fiber is then collimated into a beam using a mounted collimating lens and is transmitted through the chamber. On the opposite side of the chamber, another lens is used to focus the beam into an large diameter-core multimode fiber. The collected light is then carried to a dispersion setup, which separates the

![Figure 2. Schematic of tunable diode laser absorption spectroscopy system.](image-url)
light signals. A lens is used to focus the light from the multimode fiber onto a diffraction grating, which diffracts the light signals at different angles depending on wavelength. Once separated, the three laser signals are each focused with an off-axis parabolic mirror onto individual high speed large area InGaAs photodetectors. The voltage output from the photodetectors is recorded with a data acquisition system.

The DFB diode lasers are modulated with voltage signals from a function generator. For direct absorption measurements, the lasers are modulated with a linear-ramp at a rate of 1, 10 or 25 kHz. For the $1f$-normalized WMS-2f measurements, the lasers are modulated with a linear-ramp at a rate of 1 kHz, with a 50 kHz sinusoidal modulation superimposed. The sinusoidal waveform is recorded with the data acquisition system to provide the required frequency reference. The raw signals from the photodetectors are recorded at 2.5 MHz, and post-processed using a digital lock-in amplifier to recover the first and second harmonic components of the signal.

**IV. Results and Discussion**

**A. Preburner Combustion Products**

Absorption measurements of H$_2$O spectra (using both direct absorption spectroscopy and wavelength modulation spectroscopy, WMS) were made in the combustion products generated by the preburner, without flow through the main injector. By utilizing the existing rocket assembly in the preburner-only configuration, as detailed in Section II, high pressure, high temperature lineshape calibration data has been obtained for the H$_2$O transitions targeted in this study. These calibration measurements are necessary to refine transition parameters needed in the analysis of the rocket absorption measurements, particularly the collisional-broadening parameters. The collimated laser beam from the diode laser system was transmitted through the main chamber at approximately 5.6-in. downstream of the injector face, passing through the hot combustion products of the preburner. The temperature of the flow was measured with the thermocouple rake detailed Section II. The thermocouple junctions were positioned at the centerline of the chamber, just slightly downstream of the traversing laser beam. From these thermocouple measurements, the temperature non-uniformity ($\Delta T$) was determined to be less than $\pm 50 \, ^\circ R$, and an average of the three thermocouples was taken as the mean temperature of the flow field.

Two cases were utilized to make spectral measurements. The first was oxygen and hydrogen combusted in the preburner at a mixture ratio of 2.1, with helium dilution introduced downstream into the preburner chamber. The second case was oxygen and hydrogen combusted in the preburner, again at a mixture ratio of 2.1, this time with excess hydrogen introduced downstream (for a resulting mixture ratio of 0.72). These conditions result in two different mixture compositions at elevated temperature (1400 °R) and pressure that are then utilized to make spectral measurements. The first case yields a mixture of H$_2$O, H$_2$ and He, and the second case a mixture of H$_2$O and H$_2$.

Figure 3 shows the spectra of the preburner combustion products measured by direct absorption at various pressures ranging from atmospheric to 750 psia. The effects of collisional-broadening of the measured H$_2$O spectra are clearly visible in the plots, with the absorption feature becoming much less distinct as pressure is increased.

To determine the broadening parameters of the individual perturbing species, first a Voigt profile is fit to the spectra for each condition tested (see Figure 4 for examples). The contribution of Doppler broadening (function of temperature only) is calculated at the measured flow temperature, and supplied as a constraint to the best-fit Voigt profile. The collisional width is then output from the Voigt profile. The collisional width is then plotted as a function of pressure for the two mixture compositions (Figure 5). These values are fit with a linear trend line, the slope of which provides the value for $\Delta v_c/P$ needed to solve Eq. 15. The equation is first solved for the mixture case

![Figure 3. Absorption spectra measured in preburner combustion products mixture (H$_2$O+H$_2$+He) at approximately 1400 °R, sampled at various pressures ranging from atmospheric to 750 psia.](image-url)
involving only H$_2$O and H$_2$. The self-broadening parameter of H$_2$O and the temperature exponent are taken from published values, and the equation is solved to give the broadening parameter of H$_2$. Note that the temperature exponent, $n$, is assumed to be the same for all species, and is not measured here. With the broadening parameter of H$_2$ known, Eq. 15 is again solved, this time for the mixture of H$_2$O, H$_2$ and He to isolate the broadening parameter of He. The measured broadening parameters, as well as the other values utilized to determine the parameters, are summarized in Table 3.

It is important to note that the values of $\gamma_{H2}$ and $\gamma_{He}$ depend strongly on the temperature-exponent, $n$, used to solve the equations. Therefore, these values should always be used together. If an updated value for the temperature exponent, $n$, becomes available, the broadening-parameters would need to be recalculated using the new $n$ value. Additionally, while the values of both H$_2$ and He broadening parameters are much smaller than the self-broadening parameter for H$_2$O, the more relevant aspect is the product of broadening parameter and mole fraction of the mixture component. Since the mole fractions of H$_2$ and He in the rocket combustor are typically much greater than the mole fraction of H$_2$O, the broadening resulting from collisions of H$_2$O with these species cannot be neglected.

The values presented in Table 3 are those used in the simulations to derive temperature values from absorption measurements presented in this paper. Due to the absence of measured collisional-broadening parameters for all nearby transition lines, the values of $\gamma_{H2}$ and $\gamma_{He}$ in Table 3 are applied to all other neighboring transitions in our simulation analysis. To verify the validity of the measured broadening parameters, spectra are simulated using the measured broadening parameters and compared to the actual recorded spectra in the preburner combustion products. Examples of these comparisons are shown in Figure 6.

![Figure 4](image1.png)  
*Figure 4. Measured absorption spectra in preburner combustion products at 1388.1 nm and best-fit Voigt profiles for two conditions: a) $P=45$ psia (3.06 atm), $T=643$ K, $X_{H2O} = 0.072$, $X_{H2} = 0.202$, $X_{He} = 0.726$; b) $P=116$ psia (7.9 atm), $T=650$ K, $X_{H2O} = 0.088$, $X_{H2} = 0.912$.*

![Figure 5](image2.png)  
*Figure 5. Collisional widths as a function of pressure for two mixtures at elevated temperature with linear-fit: a) 1343.1 nm, b) 1388.1 nm.*
Table 3. Measured values of $\gamma_{\text{H}_2}$ and $\gamma_{\text{He}}$, along with other parameter values used in the analysis.

<table>
<thead>
<tr>
<th>Wavenumber, $\nu$ [cm$^{-1}$]</th>
<th>$S$ (296K) [cm$^{-1}$/atm]</th>
<th>$E''$ [cm$^{-1}$]</th>
<th>$n$</th>
<th>$\gamma_{\text{H}_2}$</th>
<th>$\gamma_{\text{H}_2}$</th>
<th>$\gamma_{\text{He}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7444.35 (1343.3)</td>
<td>0.0011</td>
<td>1774.7511</td>
<td>0.41</td>
<td>0.200</td>
<td>0.025</td>
<td>0.012</td>
</tr>
<tr>
<td>7203.89 (1388.1)</td>
<td>0.0693</td>
<td>742.0763</td>
<td>0.65</td>
<td>0.320</td>
<td>0.041</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Figure 6. Comparison of measured and simulated spectra at 1388.1 nm for two cases of preburner combustion products: a) $P=45$ psia (3.06 atm), $T=643$ K, $X_{\text{H}_2O} = 0.072$, $X_{\text{H}_2} = 0.202$, $X_{\text{He}} = 0.726$; b) $P=116$ psia (7.9 atm), $T=650$ K, $X_{\text{H}_2O} = 0.088$, $X_{\text{H}_2} = 0.912$.

Figure 7. Measured 1f-normalized WMS-2f signals in preburner combustion products ($\text{H}_2\text{O}+\text{H}_2+\text{He}$) at various pressures from atmospheric to 100 psia.

Figure 8. Path-integrated temperature measured with 1f-normalized WMS-2f technique in combustion chamber with background-flow only from preburner.
First and second harmonic signals using WMS were also recorded using combustion products in the preburner-only configuration. Figure 7 shows 1f-normalized WMS-2f signals for various pressures for both the 1343.3 and 1388.1 nm absorption features. An example of the derived path-integrated temperature in the preburner combustion products as a function of time is shown in Figure 8.

B. Full Rocket Combustor with Hot Background Flow

Absorption spectroscopy measurements were made in the GO₂/GH₂ rocket using the diode laser system detailed in Section III. Measurements were made at a single centerline location 3.125-in. downstream of the injector. A single chamber pressure of approximately 115 psia was targeted for this first set of experiments, with the rocket operating at four different conditions: nominal O/F of 4.25 and 6.0 undiluted and O/F of 4.25 and 6.0 with He-dilution in the main injector flows. A photograph of the rocket firing is shown in Figure 9.

Representative pressure traces are shown in Figure 10. At approximately 1.5 s, the main propellant valves are opened and upon ignition results in the rapid rise in chamber pressure. Introduction of GHe to the GO₂ line is delayed until 3.0 s. By 4.0 s, near-constant pressure operation of the rocket is achieved, which continues until about 5.4 s, when the fuel and oxidizer flows are terminated, resulting in a rapid decrease of the chamber pressure. All diode laser measurements presented in this section were recorded during the near-constant pressure operating portion of each test, starting at 4.0 seconds. In addition to the main chamber pressure, Figure 10 shows the key feed line pressures (pressures upstream of injector) for the main chamber and preburner chamber pressure.

Measurements were made using both direct absorption spectroscopy and 1f-normalized WMS-2f methods. Issues with beam steering prevented accurate measurements of temperature with the direct absorption approach. These problems were successfully overcome with the 1f-normalized WMS-2f method. A discussion of the efforts with direct absorption and the issues encountered is included here for completeness. This is followed by discussion of the 1f-normalized WMS-2f measurements and time-resolved path integrated temperature results in the rocket flowfield.

1. Direct Absorption

Direct absorption measurements were attempted in the rocket chamber at scans rates of 1.0, 10 and 25 kHz. Figure 11 shows samples raw photodetector output signals for the two resonant lasers with linear-ramp applied to the drive-current to scan the output wavelength across the absorption feature, and the fixed-current non-resonant reference laser.

Due to pressure broadening, no portion of the scan is free of absorption to allow for fitting of a baseline polynomial to give \( I_0 \). Instead, the signals were reduced to absorption profiles (Figure 12) by normalizing with a post-test baseline scan. Here, nitrogen was flowed through the chamber to provide a zero-absorption condition, and all lasers were modulated with settings identical to that during a firing.

A sample of the measured absorption features obtained with direct absorption during the constant-pressure portion of a rocket firing is shown in Figure 12. Attempts were made using the ratio of peak absorption values for the two targeted transitions to derive temperature values. However, the effects of beam steering on the signal were found to introduce large errors on the derived-temperatures.

Beam steering is a result of large gradients in the refractive index of the combusting gases. This causes the laser beam to wander and bloom.\(^{47,48}\) As a result, part of the light signal does not make it into the light collection system, leading to reduced signals which can be misconstrued as molecular absorption. The beam steering can be seen on the reference laser signals in Figure 11. Careful optical engineering was performed in an effort to mitigate the effects of beam steering (for example, tighter optical alignment, large collection fiber, thin windows to get optics...
close as possible to combustion zone). While the effects of beam steering were reduced significantly from early test series, they were not eliminated completely. The amount of beam steering was found to be less for the test cases with helium-dilution of the main injector flows, which one would expect as this dilution reduces the temperature-gradient along the laser beam pathlength by lowering the flame temperature and reducing the density-gradients.

In an effort to correct for remaining beam steering effects on the absorption signals, the non-absorbing reference laser signal was used to normalize the absorption signals. Unfortunately, this is not a perfect correction as the index of refraction of a gas or mixture is wavelength dependent, and therefore laser beams at differing wavelengths will not experience identical beam steering effects. In practice, it was found that with our specific optical setup and combustion environment, that the reference laser and the resonant lasers tracked each other to within a few percent. While this level of error on a direct temperature measurement (say from a thermocouple) might not be considered significant, it is for this technique. With direct absorption spectroscopy, measured signals are divided by one another to give absorption and subsequently temperature values, and therefore the effect of small errors become magnified. For example, on a 5% absorption signal, a 5% error in the baseline would lead to a 100% error in the measured absorption level. As a result, the direct absorption technique is not versatile in a beam steering environment. Correction for beam steering could theoretically be achieved by fitting Voigt-profiles to measured spectra and allowing the fitting routine to select the optimum baseline offset to minimize the error on the fit. However, any profile-fitting of the data creates an inherently time-averaged measurement, which is contrary to the goals of this project.

Many of the measurement-quality issues of the direct absorption method are reduced or eliminated with the $1f$-normalized WMS-$2f$ harmonic detection technique, which has been employed successfully in the rocket, and is discussed in the next section.

2. $1f$-Normalized WMS-$2f$

Temperature measurements have been made in the rocket chamber utilizing harmonic detection to record the first and second harmonics of the absorption features. A linear-ramp at 1 kHz was used to scan the lasers in wavelength across the absorption features, and a 50-kHz sine wave was added to provide the frequency modulation component needed for this technique.

As detailed in Section III, in the $1f$-normalized WMS-$2f$ technique the second harmonic signal of each laser is normalized by the first harmonic. Since both the $1f$ and $2f$ are components of the same signal, the ratio is unaffected by signal loss resulting from scattering, beam steering, window fouling, or vibrations. For the measurements presented here, the raw signals from the

![Figure 11. Raw output from photodetectors for two lasers (1343.3 nm, 1388.1 nm) scanning over absorption feature and fixed non-resonant reference laser at 1310 nm: (a) 1.0 kHz scan, (b) 25 kHz scan.](image)

![Figure 12. Direct absorption profiles for (a) 1343.3 nm and (b) 1388.1 nm, acquired with linear ramp modulation at 25 kHz.](image)
photodetectors were recorded and later post-processed with a digital lock-in amplifier (Labview) with a time-constant of 10 μs.

Examples of the 2f/1f signals are shown in Figure 13 for eight scans cycles during the constant-pressure operating period of the rocket combustor. To better visualize the 2f/1f profiles, an example of time-averaged signals are shown in Figure 14, converted from time to wavenumber-domain. Note that while a large portion of the 2f/1f feature is captured during the 1-KHz scans, in order to improve the time-resolution of the derived-temperatures, only the peak values at the center of each scan are used. It is therefore important that the signal peaks of the feature at both target wavelengths are aligned in the time-domain while the lasers are being scanned so that both peaks are captured in a single time-slice. Since only the peak values of the features are utilized to determine temperature, the time-resolution is limited only by the responsiveness of the photodetector and the data acquisition system (here, sampling was conducted at 2.5 MHz), while the repetition-rate is limited to the scanning frequency (1.0 kHz) of the lasers. By comparing the ratio of instantaneous peak values of the 1f-normalized WMS-2f signals for the two wavelengths to that predicted by the spectroscopic model (for example, Figure 15), the instantaneous path-integrated temperature can be determined.

A sample of the measured time-resolved 1f-normalized WMS-2f peak signals for both wavelengths recorded during a rocket firing are shown in Figure 16. The derived temperature as a function of time, along with the probability distribution of measured temperatures, is shown in Figure 17 for diluted and undiluted cases at O/F of 4.25. As can be seen in the temperature trace and distribution, the fluctuation in mean path-integrated temperature appears to be much less for the diluted versus undiluted condition. Comparison of the temperature as a function of time trace for the full rocket cases (Figure 17) with that measured in background-flow only configuration (Figure 8), it is evident that these fluctuations in path-integrated temperature are resulting from the main injector flow rather than the background flow.

While the purpose of this project was determine time-resolved flow temperatures, such as illustrated in Figure 17, a useful first-order method for validation of the temperature measurements is to compare time-averaged
(a) 1343.3 nm
(b) 1388.1 nm

Figure 16. Temporally-resolved 1/f-normalized WMS-2f peak height signal in rocket combustor at 115 psia: (a) 1343.3 nm and (b) 1388.1 nm.

(a) Temporally-resolved path-integrated temperature in rocket combustor at 115 psia, by 1/f-normalized WMS-2f method, 1000 Hz repetition rate with time resolution of 0.4 μs for each data point;
(b) Probability distribution for 0.50 seconds of test (500 data points).

Table 4. Mean path integrated temperatures derived from 1/f-noramlized WMS-2f measurements at nominal chamber pressure of 100 psia; 0.50 seconds averaged.

<table>
<thead>
<tr>
<th>Case</th>
<th>Nominal O/F Main Injector</th>
<th>He-Dilution Main Injector</th>
<th>Predicted Mixture Temperature* (K)</th>
<th>Measured Path Integrated Temperature (K)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>120910_0010</td>
<td>6.0</td>
<td>Diluted</td>
<td>1540</td>
<td>1532</td>
<td>-2.7</td>
</tr>
<tr>
<td>121410_0015</td>
<td>4.25</td>
<td>Diluted</td>
<td>1393</td>
<td>1338</td>
<td>-4.0</td>
</tr>
<tr>
<td>120910_0013</td>
<td>6.0</td>
<td>Undiluted</td>
<td>2103</td>
<td>1988</td>
<td>-5.5</td>
</tr>
<tr>
<td>121410_0020</td>
<td>4.25</td>
<td>Undiluted</td>
<td>1838</td>
<td>1832</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

*Calculated using Chemical Equilibrium Analysis (CEA)
results with equilibrium calculations using Chemical Equilibrium Analysis (CEA).\textsuperscript{51} For the CEA calculations, propellants to main chamber (entering the main chamber at ambient temperature) were considered to be mixed completely with the background flow (combustion products from the preburner entering the main chamber at elevated temperature) and combusted fully. The composition of the flow from the preburner was calculated independently with CEA, and the temperature as it enters the main chamber specified as 1400 °R, based on temperature measurements of the flow in the preburner-only configuration. (Note that in practice this temperature was observed to deviate by approximately ±50 °R, which introduces uncertainty into the CEA calculations. The temperature of the preburner combustion products could not be measured with thermocouples for the full-rocket configuration.)

The results of this comparison are shown in Table 4 for the four conditions tested. Measured path-integrated temperatures were averaged over 0.5-seconds during constant-pressure operation of the rocket, as indicated in Figure 10. As can be seen in the table, the time-averaged path-integrated temperatures compare very well with the predicted temperatures from CEA equilibrium calculations. The difference between measured and calculated mean temperature was found to be less than 10% for all cases.

V. Conclusion

Application of tunable diode laser absorption spectroscopy (TDLAS) to make time-resolved measurements of temperature in a moderate pressure rocket combustor has been successfully demonstrated. Utilization of this technique allows for detailed time-resolved study of the turbulent fluctuations in gaseous propellant rocket engines. Path-integrated temperature measurements achieved by using a harmonic detection technique (1f-normalized WMS-2f) have been presented for a gaseous oxygen / gaseous hydrogen uni-element rocket chamber with hot background flow at a chamber pressure of 115 psia. Four different mixture ratio conditions were studied (two diluted and two undiluted) at a single axial location, proving valuable data for examining the underlying physical combustion and mixing processes, as well providing data for validation of transient rocket combustor models. In all cases examined, the mean measured temperatures compared well predicted mixture temperatures using chemical equilibrium analysis as a first-order validation of the results.

Additional efforts are needed if this technique is to be applied successfully at higher chamber pressures and higher measurement repetition rates. It is recommended that future studies utilize the 1f-normalized WMS-2f technique rather than direct absorption, as 1f-normalized WMS-2f has been shown to be much more versatile for making path-integrated temperature measurements in a rocket combustion environment.

Acknowledgments

This work was sponsored by NASA Constellation University Institutes Project under grant NCC3-989 with Claudia Meyer as the project manager. The authors would also like to thank Mr. Larry Schaaf for his efforts in setting up and running the rocket combustion experiments.

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