



AFRL-RZ-WP-TP-2010-2055

**DIODE LASER-BASED DETECTION OF COMBUSTOR
INSTABILITIES WITH APPLICATION TO A SCRAMJET
ENGINE (POSTPRINT)**

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FEBRUARY 2010

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REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YY) February 2010		2. REPORT TYPE Journal Article Postprint		3. DATES COVERED (From - To) 10 April 2007 – 10 September 2008	
4. TITLE AND SUBTITLE DIODE LASER-BASED DETECTION OF COMBUSTOR INSTABILITIES WITH APPLICATION TO A SCRAMJET ENGINE (POSTPRINT)				5a. CONTRACT NUMBER In-house	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Campbell D. Carter and M.R. Gruber (AFRL/RZAS) G.B. Rieker, J.B. Jeffries, and R.K. Hanson (Stanford University) T. Mathur (Innovative Scientific Solutions, Inc.)				5d. PROJECT NUMBER 2308	
				5e. TASK NUMBER AI	
				5f. WORK UNIT NUMBER 2308AI00	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Propulsion Sciences Branch (AFRL/RZAS) Aerospace Propulsion Division Air Force Research Laboratory, Propulsion Directorate Wright-Patterson Air Force Base, OH 45433-7251 Air Force Materiel Command, United States Air Force Stanford University Stanford, CA 94305 Innovative Scientific Solutions, Inc. Dayton, OH 45440				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RZ-WP-TP-2010-2055	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Propulsion Directorate Wright-Patterson Air Force Base, OH 45433-7251 Air Force Materiel Command United States Air Force				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RZAS	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RZ-WP-TP-2010-2055	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES Journal article published in <i>Proceedings of the Combustion Institute</i> , Vol. 32 (2009). PA Case Number: 88ABW-2007-0554; Clearance Date: 28 Nov 2007. © 2009 The Combustion Institute. The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.					
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15. SUBJECT TERMS Scramjet, instability, unstart, combustor, sensor					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON (Monitor) Campbell D. Carter 19b. TELEPHONE NUMBER (Include Area Code) N/A
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			

Diode laser-based detection of combustor instabilities with application to a scramjet engine

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Abstract

Fluctuations in temperature non-uniformity along the line-of-sight of a diode laser absorption sensor in a model scramjet are found to precede backpressure-induced unstart (expulsion of the isolator shock train). A novel detection strategy combining Fourier analysis of temperature time series to determine low-frequency heat release fluctuations with simultaneous measurements of multiple absorption features of H₂O to identify temperature non-uniformities was applied to the scramjet combustor. Time-resolved absorption is measured using wavelength modulation spectroscopy for three transitions chosen with different temperature-dependent absorption characteristics. The line-of-sight (LOS)-averaged temperature inferred from the ratio of absorption from one pair of transitions is highly sensitive to low-temperature non-uniformities along the absorption path while the other ratio is less sensitive. The fraction of fluctuations in the range $1 < f < 50$ Hz is determined from short-time Fourier transforms (STFTs) of the measured temperatures from both transition pairs. The ratio of these fractions provides a robust measure of the low-frequency fluctuations in temperature non-uniformities in the flow. Measurements in a scramjet test rig indicate a distinct increase in low-frequency fluctuations of low-temperature gases several seconds before the isolator shock train is forced out of the inlet by heat addition to the combustor. Though the precise cause of the fluctuations remains unknown, the detection method shows promise for use in control schemes to avoid back pressure-induced unstarts.

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Keywords: Scramjet; Instability; Unstart; Combustor; Sensor

1. Introduction

To optimize performance or minimize emissions from many of today's practical combustion

systems, designers are increasingly pushing operating points toward the limits of combustor stability. For scramjet engines, thrust is maximized when fuel is increased to a level just before the isolator shock train is forced out of the inlet by backpressure due to combustion [1]. For flight tests and engines operating in a freejet, discharging the isolator shock train results in inlet unstart, which causes a significant decrease in captured air mass

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by the engine and potentially catastrophic failure. Unstart is a highly unsteady process, owing to unstable phenomena present in the scramjet near unstart [2 and references therein]. In terms of the inlet and isolator, several researchers [2–5] have shown that increasing combustor backpressure eventually leads to severe boundary-layer separation throughout the inlet, which obstructs the core flow and causes unstart. Strong pressure oscillations associated with this process have been measured in the inlet and isolator both before and after unstart [4,5]. The combustor also has strong unsteady characteristics associated with its operation. Numerical analyses for several configurations of a transverse fuel jet upstream of a cavity flameholder found several sources of instability – flow disturbances stimulated by shear-layer instability, injected-jet destabilization by disturbances from the downstream flameholder, and an unstable Mach reflection formed above the jet due to flow unsteadiness for cases of strong combustion that leads to strong pressure fluctuations [6]. Unfortunately, no studies have been performed on the interaction of the combustion process with inlet transients during unstart. However, all of the instabilities above result in large-scale flow fluctuations which are certain to affect the time-dependent behavior of the combustion process.

Thus far, research on the detection and control of combustion instability has focused primarily on subsonic turbulent combustors [7]. NO_x emission regulations on gas turbines have driven the use of fuel–lean stoichiometries. Unfortunately, operation of turbulent combustors in lean regimes increases susceptibility to thermoacoustic instabilities [8] and lean blowout [9], both of which result in large-scale fluctuations in pressure and temperature in the combustor.

The primary methods employed by researchers for detecting and controlling unstable fluctuations have been acoustic techniques [10,11], light emission from combustion radicals [12], and line-of-sight (LOS) absorption techniques [13–15]. Each technique offers benefits and drawbacks. Acoustic techniques generally use low cost and easy-to-use pressure transducers or microphones but can suffer from a lack of specificity due to background noise and low spatial resolution. Emission techniques employ photodetectors, but often lack useful spatial resolution and can suffer from background light emission and interference from other species. Line-of-sight absorption sensors rely on more expensive tunable diode lasers (TDLs) and turnkey sensor packages are not yet available. However, TDL-LOS techniques have the potential for selected spatial resolution and, as will be discussed below, can be designed to detect specific aspects of interest in the flow (such as fluctuations in localized heat release).

Previous fluctuation sensors based on LOS absorption demonstrated the use of a near-IR

TDL to measure time-resolved temperature from the ratio of water vapor absorption at two wavelengths and to actively suppress lean blowout and thermoacoustic instabilities in a swirl-stabilized combustor [13,14]. The sensor revealed an increase in low-frequency temperature fluctuations near lean blowout due to localized flame extinction and re-ignition, and used this warning to actuate a fuel valve to avoid blowout. Palaghita and Seitzman [15] used an external-cavity diode laser for pattern factor sensing in a stratified methane–air combustor. Their sensor measures water vapor absorption at three wavelengths. Based on the interaction of temperature non-uniformity along the absorption path with the different nonlinear temperature dependence of each absorption feature, they defined a non-uniformity parameter that increases with stratification and may provide a suitable control variable for creating more uniform combustor properties.

In the current work, the application of a three-wavelength, near-IR diode laser sensor to a scramjet test rig for measurements during unstart presents two key advances in fluctuation sensing for combustion instabilities. First, the detection strategy extends the ideas in [13–15] to create a more robust method. The use of fast temperature measurements and short-time Fourier transforms (STFTs) to track frequency components in the flow is made more robust by taking the ratio of STFTs for the measured temperature of two absorption feature pairs with different temperature dependences. This ratio reduces sensitivity to degradations in signal-to-noise ratio (SNR) and to certain combustor transients (e.g. during startup). Furthermore, through the temperature dependence of the selected absorption features, this ratio can isolate specific aspects of interest in the flow; e.g. low-frequency fluctuations of low-temperature non-uniformities along the absorption path.

The second key advance of this work is the application of an optically-based fluctuation detection strategy to measurements in a supersonic flow. The travel of acoustic waves in supersonic flows is complicated by the speed of the moving gases. Wall pressure measurements are subject to acoustic phenomena in subsonic boundary layers, while pressure waves emanating from events in the center of the combustor may not be detected at the wall until they traverse the supersonic gas and strike the wall downstream of the event. Laser absorption strategies that employ light, however, are capable of capturing fluctuations along the beam path.

This paper is presented in three parts: first, the sensor and fluctuation detection method are introduced. Second, a description of the scramjet test facility at the Air Force Research Laboratory is given. Finally, data is shown from a representative stable scramjet combustor run, and from one in

which the isolator shock train was forced upstream of the engine throat in the direct-connect scramjet rig (termed unstart throughout the paper). The data show that low-frequency fluctuations of low-temperature non-uniformities downstream of the combustor flameholders increase several seconds before unstart. Although the precise cause of these fluctuations is not yet understood, these fluctuations appear to be a precursor to unstart in scramjets and have potential for use in control strategies.

2. Temperature fluctuation detection with absorption spectroscopy

This section discusses the use of diode laser-based absorption spectroscopy to detect frequency-resolved temperature fluctuations in non-uniform gases. The method can isolate fluctuations in a specific temperature range, for example the lower temperature gases of a non-uniform region. The method can be further tuned to focus on high- or low-frequency fluctuations in the temperature range of interest, and made robust against noise and certain transients by using multiple absorption features.

2.1. Detection of specific temperature non-uniformities

This section will describe the method of inferring path-averaged temperature in non-uniform environments using multiple absorption feature ratios to detect changes in temperature non-uniformity.

Wavelength modulation spectroscopy with second harmonic detection (WMS-2f), a derivative method of direct absorption spectroscopy, was chosen for the measurements because of its superior noise-rejection ability in harsh environments [16]. The WMS-2f signal is normalized by the first harmonic (1f) detector signal, because this nullifies variations in laser power, scattering, and window fouling. In addition, this normalization strategy provides calibration-free (absolute) measurements of temperature and species concentration when the laser tuning characteristics are known [16–18]. The details of this technique [17] and the sensor design [18] have been described elsewhere, and will be reviewed only briefly here.

Temperature is inferred from the ratio of 1f-normalized, WMS-2f signals for two absorption features. To make sensitive temperature measurements, one must choose absorption features with different temperature-dependent absorption characteristics. The temperature response of a particular absorption feature is determined by its lower-state energy (E''). Absorption features with a low E'' absorb strongly at low temperature, when a larger proportion of molecules populate

low energy states. The same is true for high E'' features at high temperatures. Thus temperature-sensitive ratios are formed with features having widely different E'' . The temperature dependence of the three features used in this work with E'' ranging from 79 to 2952 cm^{-1} are shown in Fig. 1.

When the absorption pathlength is non-uniform, the path-averaged nature of absorption spectroscopy makes signal interpretation more complex [19–21]. The nonlinear temperature response of each feature in a particular ratio produces a different sensitivity of that ratio to low- or high-temperature non-uniformities along the absorption path. By taking advantage of this characteristic, one can select feature ratios which are highly sensitive to, for example, low-temperature gases in the non-uniform environment, and feature ratios which are insensitive to low-temperature gases. The difference in the path-averaged inferred temperatures from these ratios will yield information about the relative magnitude of low-temperature non-uniformities along the measurement path.

This is illustrated in Fig. 2, which plots the inferred temperature using two different ratios for a simulated non-uniform path made up of two regions—one at 600 K and one at 1500 K. Along the abscissa, the ratio of pathlength at 600 K/1500 K is varied. At the left and right ends of the abscissa, the path is uniform at 1500 and 600 K, respectively, and the measured temperature using both ratios is identical. However, for non-uniform cases the inferred temperature using the two absorption ratios differs—the temperature using a ratio of low E'' and a high E'' features (labeled mixed E'') is artificially low, while the temperature using a ratio of two relatively high E'' features (labeled high E'') is less affected. In this case, pockets of low-temperature gas along the absorption path will affect the inferred temperature using the mixed E'' ratio by as much as 18% more than the inferred temperature using the high

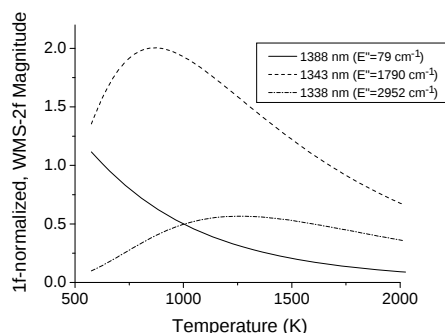


Fig. 1. Simulated 2f/1f signal for the three probed H_2O spectral features. $P = 0.85$ atm, $x_{\text{H}_2\text{O}} = 0.11$, $L = 23$ cm. Laser-specific characteristics [17]: $a \sim 0.07 \text{ cm}^{-1}$, $i_0 \sim 0.10$.

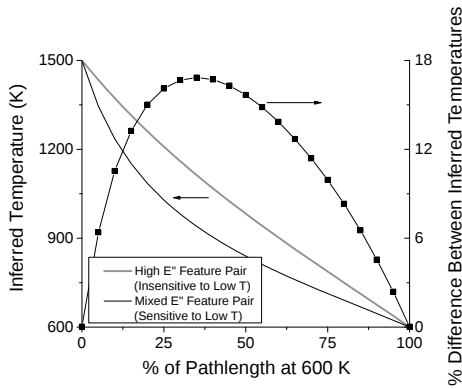


Fig. 2. Simulated path-averaged inferred temperature using two spectral feature pairs for a non-uniform absorption path comprised of a section at 600 K and a section at 1500 K. The portion of the path that is at 600 K is varied with the remainder of the path at 1500 K.

E'' ratio for this particular example of non-uniformity. Through careful selection of absorption feature pairs, the experimentalist can tune the sensor to be responsive to different types of non-uniformities along the absorption path.

2.2. Detection of fluctuations in a flow field with non-uniform temperature

The goal of any sensor is to create a robust, high-contrast signal for the target measurement property. The sensor signal should be robust in that it responds only to changes in the target property, and high-contrast in the sense that it undergoes a large change per unit change in the target property. The goal of the current sensor is to measure low-frequency fluctuations in the low-temperature non-uniformities of the scramjet flow. We want to look not just at the boundary layer that is always present, but rather the instability in that boundary layer, and in the unburned or partially burned gases in the core flow due to combustor instabilities.

To achieve this goal, two absorption feature ratios are selected such that one ratio is sensitive to low-temperature non-uniformities in the flow and the other ratio is not (Section 2.1 above). Next, we design a data reduction scheme to deliver a robust, high-contrast signal for low-temperature fluctuations measured with these two absorption ratios. Since the evolution of temperature in the scramjet engine is nonstationary (statistics change with time), a frequency analysis technique that is capable of capturing the temporal development of the frequency content is necessary. The simplest of these techniques, and the one used here, is the short-time Fourier transform (STFT), which is a regular Fourier transform

applied to a finite, moving time window of the signal of interest. If $x(t)$ is the signal of interest, the STFT can be represented by,

$$S_x(t, f, \tau) = \int_{t-\tau}^t x(\tau) \cdot e^{-2\pi i f \tau} d\tau \quad (1)$$

where f is frequency. The squared magnitude of the STFT is called a spectrogram and represents the frequency content of the signal as a function of time. The choice of integration limits is a trade-off between temporal resolution and frequency resolution—shorter windows give better temporal resolution, but coarser frequency resolution. For the data presented in this paper, $\mathcal{T}$ (and hence the length of the window) was chosen to be 0.5 s. Also note that the choice of ' t ' as the upper integration limit assumes no knowledge of future events and thus simulates the behavior of a real-time implementation of the STFT calculation. Other time-frequency methods could also be applied to achieve similar results, such as the wavelet transform and Wigner-Ville distribution [22].

The spectrogram has two key drawbacks from the standpoint of a detection system for application in control—it is two-dimensional, and tracking the time evolution of individual frequency components in the spectrogram may not deliver strong contrast for instabilities that do not exhibit a strong pattern at one frequency. It is therefore useful to create a one-dimensional representation that extracts information from a range of frequencies. To accomplish this, a range of frequencies of interest is chosen, $f_l \rightarrow f_h$, and the magnitude of the STFT in that range is summed for each time step. This is normalized by the sum of the magnitude of the STFT at all frequencies to obtain the fraction of frequency content in the range of interest, F :

$$F(f_l, f_h, t, \mathcal{T}) = \frac{\sum_{f_l}^{f_h} |S_x(t, f, \mathcal{T})|}{\sum_{f=0}^{f_{\text{sensor max}}} |S_x(t, f, \mathcal{T})|} \quad (2)$$

For this work, the interest is in low-frequency temperature fluctuations. Thus the fraction of frequency content in the range $f_l = 1 \rightarrow f_h = 50$ Hz is chosen.

Harsh combustion environments contain sporadic noise sources such as window fouling, periods of heavy beam steering, or beam attenuation from particulates in the flow. Although these sources are accounted for by 1f-normalization, they can still degrade signal-to-noise ratios. In addition, startup transients in the scramjet lead to large-scale *uniform* temperature fluctuations. These factors can lead to increased frequency content in the fluctuation measurement that is not caused by fluctuations of low-temperature non-uniformities. The final step then in creating a robust signal is to minimize these unwanted influences. This can be achieved by rationing the fraction of frequency content, F , created from the measured temperature using the low-temperature

sensitive ratio with the F created from the measured temperature using the insensitive ratio:

$$R(f_l, f_h, t, \mathcal{T}) = \frac{F(f_l, f_h, t, \mathcal{T})_{\text{Low T sensitive}}}{F(f_l, f_h, t, \mathcal{T})_{\text{insensitive}}} \quad (3)$$

Large-scale *uniform* temperature fluctuations and degradations to signal-to-noise ratio will affect both temperature measurements similarly; however fluctuations in low-temperature non-uniformities will only affect F for the low-temperature sensitive feature pair. As will be shown in Section 4, taking the ratio of F from $1 < f < 50$ Hz for the two different measured temperatures eliminates common-mode transients while retaining the specific low-frequency fluctuations in low-temperature gases preceding unstart.

Using the method presented above, one is able to directly tune the sensor to detect only fluctuations of temperature non-uniformity. The experimentalist can choose to look at fluctuations in high or low temperature gases through the choice of absorption features. The frequency range in the summation of the fractional STFT can be changed to develop contrast in different frequency windows. Finally, taking the ratio between two fractional STFTs focuses on fluctuations in temperature non-uniformity along the absorption path.

2.3. Optical setup

The optical setup is presented in detail in [18], and will be summarized briefly here. The light from three fiber-coupled DFB diode lasers tuned to the selected transitions is combined onto one single-mode fiber using a fiber multiplexer. The fiber carries light from the sensor setup to a collimating lens. The beam is pitched through wedged quartz windows 16.5 cm upstream of the exit plane of the combustor to a large diameter catch lens. The lens focuses the light onto a 400- μm multimode fiber which terminates at the dispersion and detection system. The individual colors of the beam are separated by a hybrid-demultiplexing technique that combines wavelength-demultiplexing using a grating with frequency-demultiplexing using a

lock-in amplifier [18]. All laser drive signal generation and data collection is performed by a single PC.

3. Scramjet facility

The scramjet test rig used for this study is located in a high-enthalpy, continuous-flow, direct-connect supersonic combustion facility at AFRL, Wright-Patterson AFB, Ohio. The facility supplies 13.6 kg/s of air at up to 920 K and 5.2 MPa. A methane-fueled vitiator further increases the temperature and pressure to the desired experimental conditions, and oxygen is added to re-establish ambient levels. Interchangeable facility nozzles accelerate the flow to supersonic speeds. Here, a Mach-2.84 nozzle simulates flight Mach numbers of 5–5.5, and a distortion-generator simulates the effects of flight conditions on the combustor inlet [23]. Further information on the scramjet facility can be found in [24].

The scramjet flowpath is shown in Fig. 3. It consists of isolator, combustor, and expansion sections. The combustor has fuel injector banks in multiple locations, so many fuel-injection configurations can be tested. For the results shown here, fuel was injected upstream of a cavity flameholder on the body side of the flowpath. Additional fuel was added between the cavity and rear-facing step flameholders on both the body and cowl sides of the flowpath. Overall fuel/air equivalence ratios of $\phi = 0.6$ –0.9 were tested with unstart occurring for the higher values.

The combusting gases continue past the flameholders to the optical measurement location in the expanding section. The scramjet flowpath is heavily instrumented with pressure and thermocouple taps, which are sampled at ~ 1 Hz throughout each run.

4. Scramjet results

The diode laser sensor was used to monitor 99 combustor runs of the scramjet test rig. Here, an

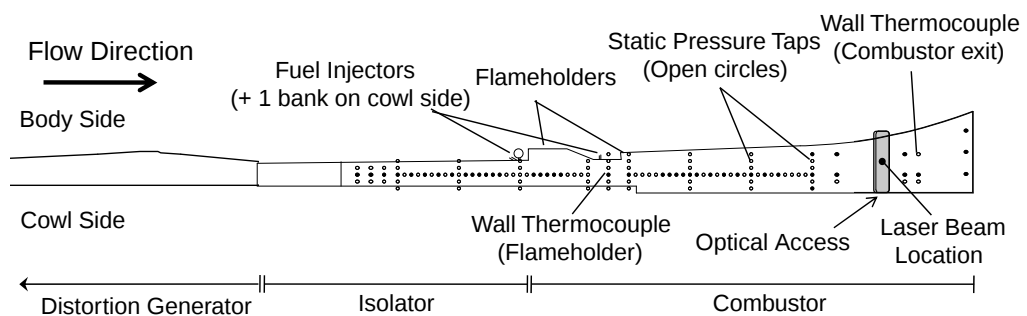


Fig. 3. Schematic of AFRL continuous-flow, direct-connect scramjet flowpath.

unstable case in which unstart occurs is compared with a representative stable case to demonstrate the utility of the fluctuation detection method. All operating parameters for the scramjet are identical for the two cases shown, except the overall fuel/air equivalence ratio, which is $\phi \approx 0.7$ for the stable case and $\phi \approx 0.85$ for the unstable case.

The average gas temperatures measured with multiple absorption feature ratios for the stable and unstable cases are shown in Fig. 4. Because a long time history is shown, the measured temperatures have been filtered with a 100-Hz low-pass filter to suppress outliers that increase the appearance of noise in dense plots. Both combustor runs begin with only vitiated air at ~ 575 K passing the measurement location. Combustor fuel injection begins at approximately 24 s. No ignition source was used for these measurements, so the autoignition and flame stabilization process occurs for 6–7 s as the flame develops across the combustor and approaches steady-state. Gas temperatures appear to plateau for several seconds when a sudden blowout/re-ignition event occurs for the unstable $\phi \approx 0.85$ case. The inset of Fig. 4 shows the blowout/re-ignition event at the full sensor sampling rate of 4 kHz. After this event the average gas temperature at the measurement location is reduced for the $\phi \approx 0.85$ case.

The isolator pressure history for the unstable combustor run is used to compare the timing of the blowout/re-ignition event with unstart. The scramjet flowpath contains 248 pressure taps that record the unstart by tracking the location of the isolator shock train. Due to the 0.9-Hz pressure-sampling rate, there is an uncertainty in the timing of this rapid event. In addition, the diode laser data system was not digitally synchronized with the pressure-acquisition system introducing an additional ± 0.5 s uncertainty. Finally, a -0.2 -s uncertainty is added to account for acquisition time lag and damping in the pressure lines. This conservative uncertainty is represented by a 2.3-s

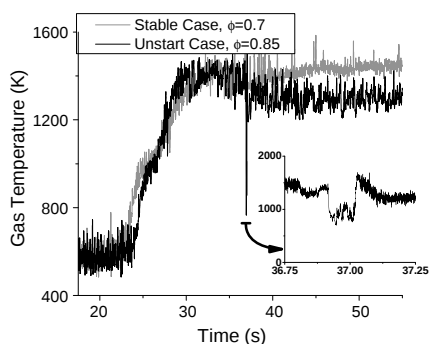


Fig. 4. Full-run temperature profiles for stable and unstable cases (100-Hz filtered). Inset shows blowout at full sensor sampling rate (4 kHz).

window during which the unstart event occurred, which is plotted over the laser sensor data in Figs. 5–7.

Figure 5 shows the gas temperature measured with the high E'' and the mixed E'' absorption feature pairs during the late-startup transient and unstable combustion periods. Two key features are evident. First, even accounting for the uncertainty in the exact timing of the inlet unstart, the blowout occurs before the inlet unstart. Second, looking at the mixed E'' measurement 4.8 s before unstart, one can see a marked decrease in temperature and an increase in measured temperature fluctuations that are not as apparent in the high E'' measurement. Recall from Fig. 2 that the high E'' ratio is much less sensitive to low-temperature gases in a non-uniform path than the mixed E'' ratio. This suggests that a marked increase in low-temperature gases as well as fluctuations in these gases occurs before unstart.

To quantify this increase, the fractional STFT described in Eq. (2) is plotted for both ratios in

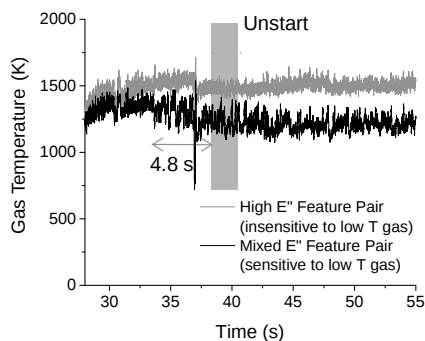


Fig. 5. Measured temperature with individual absorption feature pairs. Unstart (observed in wall pressure data) occurred during the gray time window.

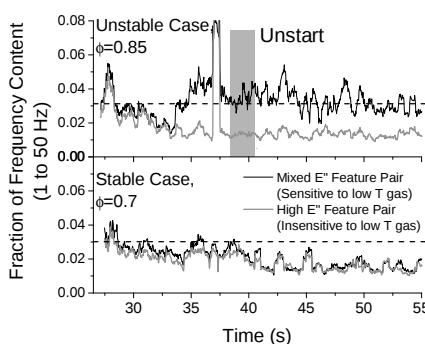


Fig. 6. Fraction of frequency content in $1 < f < 50$ Hz for an STFT of the temperature measured with each absorption feature pair.

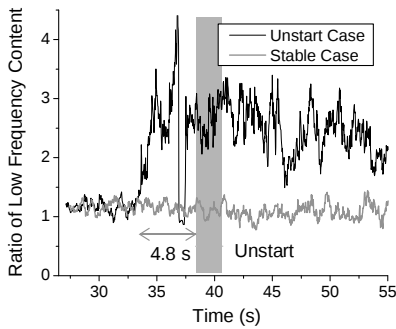


Fig. 7. Ratio between fractional STFT of each absorption feature pair. Note the unstart time window does not apply to the stable case.

Fig. 6. The increase in frequency content in the $1 < f < 50$ Hz range for the mixed E'' ratio is apparent prior to unstart. However, by only examining the mixed E'' line pair, one cannot distinguish between the increased transients during startup and the onset of the particular instability that proceeds unstart. An arbitrary threshold is plotted in Fig. 6 to illustrate this point. At early times, the low-frequency content is similar in magnitude to when the instability begins. Even for the stable combustor case (bottom panel of Fig. 6), the fractional STFT is large during startup transients.

To distinguish between the increased transients during unstart and the fluctuations preceding unstart, the ratio between the fractional STFTs using different line pairs is taken according to Eq. (3). This rejects common-mode transients in the two signals and, as shown in Fig. 7, increases the contrast of the fluctuations of LOS temperature non-uniformity. From this figure, the increase in low-frequency fluctuations in low-temperature gases in the non-uniform combustor exit clearly begins ~ 4.8 s before unstart. This phenomenon was recorded for all cases that experienced unstart, with varying initiation times up to 10 s before unstart. The blowout/re-ignition event was not always present.

It is presently unclear what physical processes are causing the increase in low-frequency fluctuations prior to unstart. As discussed in Section 1, isolator boundary-layer growth and separation are associated with unstart as well as several potential instabilities for transverse fuel jets at increased heat-addition rates. Interaction between the combustor and isolator is also likely to occur, but has not been studied. Overall, the likelihood is high for large-scale flow-instabilities to exist during the unstart process. Because the increase in low-frequency fluctuations begins in advance of unstart, one can see the potential utility of the ratio of fractional STFT information from two absorption line pairs as a control variable. The

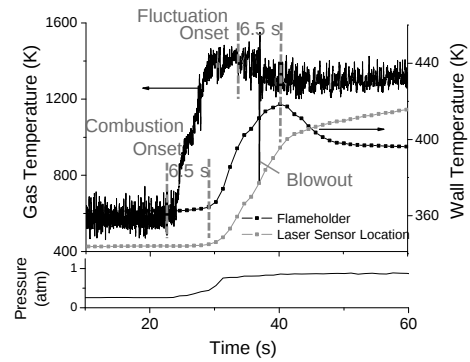


Fig. 8. Full-run gas temperature, wall temperature, and pressure for unstable case. Wall temperature exhibits time lag, but inflection points agree with gas temperature events.

variable could be used to limit fuel flow to the combustor, or modify the distribution of fuel among a series of injection sites, at the onset of fluctuations and thereby avoid a back-pressure induced unstart.

Figure 8 shows the average gas temperature plotted with 0.9-Hz static pressure and wall temperature data near the optical measurement location. No distinct change is seen in the wall pressure before or after unstart. However, the wall temperature data, which experiences a 6.5-s lag with respect to the laser measurement due to thermocouple response and wall heat capacity, show inflection points that match the laser data.

5. Summary and conclusions

A method to detect frequency-resolved temperature fluctuations using a diode laser-based sensor was developed and applied to the scramjet test rig at AFRL. Ratios of measured quantities can be taken to isolate the sensor response to low-frequency fluctuations in temperature non-uniformity along the absorption LOS. The WMS-2f signal is normalized by the 1f signal to suppress perturbations to laser transmission (i.e. beam steering, window fouling, scattering, etc.). The LOS-averaged temperature is inferred using the ratio of absorption on two spectral transitions, which suppresses variation/fluctuation in water vapor concentration. Inferring different temperatures based on pairs of water vapor features with different sensitivities to low-temperature non-uniformities along the absorption path enables differentiation of these non-uniformities from uniform changes in temperature. A Fourier analysis (STFT) of the time-resolved temperature provides a measure of the temperature fluctuations. Summing the magnitude of the STFT of measured

temperature in the $1 < f < 50$ Hz range and normalizing by the total sum of the STFT produces a measure of the fraction of frequency content at low frequency, which provides a monitor of stability. Taking the ratio of the fraction of low-frequency content for the two measured temperatures with different sensitivity to non-uniformity focuses the sensor specifically on low-frequency fluctuations in temperature non-uniformity, eliminating sensitivity to overall temperature fluctuations and to changes in SNR. The correlation of local temperature with local heat release, the ability to make high-bandwidth measurements to capture temperature (heat release) fluctuations, and the use of spectroscopic line selection to identify non-uniformities of the temperature (heat release) in the combustor, all serve to confirm the potential of diode laser absorption sensors for a wide variety of new control strategies.

The first demonstration of this new diagnostic strategy in the high-speed ducted flow of the model scramjet at AFRL yielded several interesting conclusions/observations:

1. There is a distinct increase in low-frequency fluctuations of low-temperature non-uniformities in the combustor several seconds before the occurrence of back-pressure induced unstart.
2. The onset of fluctuations preceding unstart corresponds to changes in wall thermocouple measurements in the combustor, which lag the optical sensor by 6.5 s.
3. The specificity and fast time response of this diagnostic strategy confirm its potential utility as a control variable to adjust combustor flow and fueling properties to achieve high performance while avoiding back-pressure induced unstart.

Acknowledgments

This research was sponsored by the Air Force Office of Scientific Research, Aerospace and Materials Science Directorate, with Julian Tishkoff as technical monitor. The authors thank Andrew Fahrland and Andree Houle for help conducting experiments at AFRL. Document WPAFB 07-0554, approved for public release; distribution unlimited.

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