Dynamic Pressure Characterization of a Dual-Mode Scramjet

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1 Introduction

Combustion mode transitions in dual-mode combustors typically occur during vehicle acceleration (ramjet-to-scramjet) or in case of thermal choking due to excessive heat addition (scramjet-to-ramjet). These highly unsteady processes inherent to dual-mode systems can affect flame stability and generate pressure fluctuations that may be undesirable for engine performance. Characterizing combustion mode transitions is therefore critical to the understanding of their flow physics and is relevant to the advancement of future hypersonic propulsion systems. Contributing to this overarching goal is the main motivation behind this work while adding to the existing experimental database [1-5] the primary objective.

This study experimentally characterized a hydrogen fueled dual-mode scramjet combustor using transverse wall injection. The laboratory scale-scramjet combustor had a bottom wall cavity used for flame holding and combustion stabilization [6]. Combustor equivalence ratios spanning both scramjet and ramjet operating modes were tested using a vitiated-air heater facility simulating a Mach 4.4 flight condition (enthalpy based). Static wall pressure measurements were gathered to establish combustion mode at the different fueling conditions. Dynamic pressure measurements and high-speed Schlieren imaging were the main experimental diagnostics used to track the high speed reacting flows through the transitional regime tested.

2 Experimental Setup

The scramjet fuel injection experiments were performed using a direct-connect vitiated-air facility at the University of Maryland's Propulsion Research Laboratory. This apparatus generates a high enthalpy flow required to simulate scramjet flight conditions by pre-heating air upstream of the test section via in-stream combustion with hydrogen fuel. Oxygen replenishment was performed upstream of the heater fuel injection location to preserve the atmospheric oxygen mole fraction content of the flow entering the supersonic combustor downstream. Flow conditions generated by this facility simulated a flight Mach 4.4 flight number on a total enthalpy basis (18.5 km altitude reference).

A close up schematic of the flow path connected to the vitiated-air heater is illustrated in Figure 1. A supersonic half-nozzle expanded the high enthalpy flow into an isolator section with an inlet Mach number M_2~1.9. This isolator was a constant area duct with a square cross section and a 12.7 *mm* duct height, *H*.

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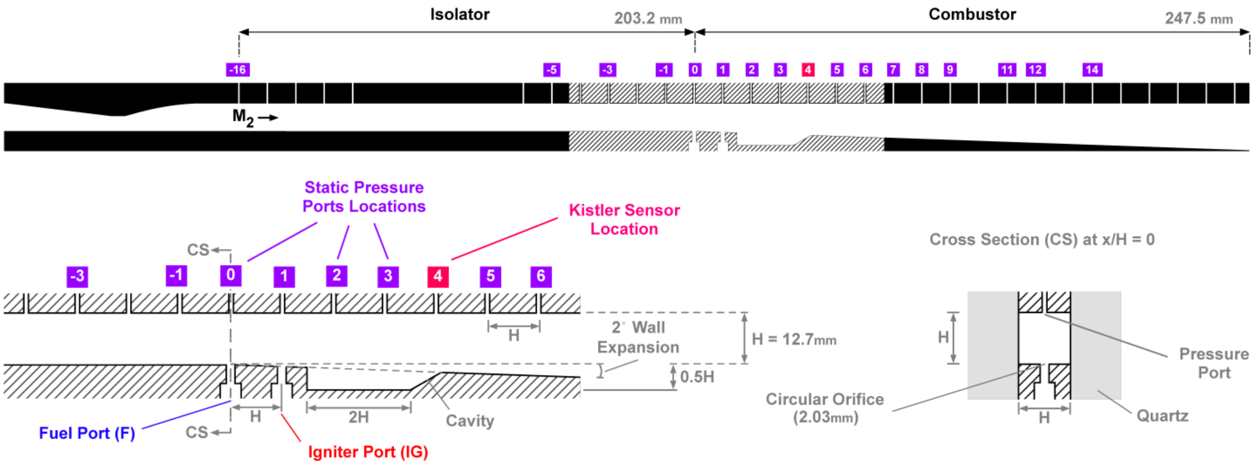

Figure 1. Cross-sectional schematic of flow path and detailed views of combustor test section.

Table 1. Experimental test conditions.

	Vitiated Heater Exit			Isolator (x/H = -16)	Combustor (x/H = 0)	
Case	**P0,** *kPa*	**T0,** *K*	**m,** *g/s*	P_2, *kPa*	m_{H2}, *g/s*	**Φ**
1	676.4	1131.1	68.8	87.2	0.08	0.04
2	680.0	1121.0	69.2	87.1	0.17	0.08
3	684.4	1117.7	69.7	87.8	0.21	0.10
4	681.9	1119.3	69.4	86.8	0.26	0.12
5	680.2	1133.4	69.2	87.5	0.30	0.14
6	677.4	1119.5	68.9	86.7	0.34	0.16
7	671.7	1119.2	68.3	86.2	0.42	0.20

The combustor section was a constant width duct with a diverging bottom wall expanding at a 2° rate. At the combustor inlet (x/*H* = 0), a circular 2.03 mm diameter orifice, *D*, was used for transverse fuel injection from the bottom wall. A second orifice with diameter *D* located 1*H* downstream was used to inject stoichiometric hydrogen-oxygen combustion products to ignite the main flow. The angled-back cavity used as a flame holder in this study was designed after the work by Yu et. al. [7] and was placed 0.5*H* downstream of the igniter port. Two 1*H* thick quartz windows were adapted as combustor side walls to allow flow visualization.

Gaseous hydrogen was the fuel of choice for the experiments. Seven different fuel flow rates were tested using room temperature hydrogen metered using choked flow orifices. Experimentally recorded gas flow rates and the assumption of complete combustion in the vitiated-air heater were used to establish a scramjet equivalence ratio (Φ) for each fuel flow rate tested. Fuel injection spanned a period of four seconds and was initiated simultaneously with the igniter, which was only operational for half a second and then shut-off. Table 1 summarizes the experimental conditions recorded for each test.

Static and dynamic pressure measurements of the reacting flow were recorded along with high-speed schlieren visualizations to characterize the flow. Static pressures were obtained at a sampling rate of 25 Hz along the upper wall of the isolator (4 locations) and combustor (12 locations) using a Scanivalve DSA-

3217 Digital Sensor Array. This device consisted of temperature compensated piezo-resistive pressure sensors with a pneumatic calibration valve with a 0 -1.5 MPa range. A water-cooled, high frequency response Kistler pressure transducer was used to obtain dynamic pressure measurements above the cavity (Figure 1). The 20KHz signal recorded was hardware filtered between 0.01 – 10KHz and a FFT routine was used to obtain the dominant modes and their amplitudes. High speed schlieren flow visualizations were captured using a Phantom v2512 at a framing rate of 40KHz. A Cavilux Smart laser system with a 640 nm wavelength was used as a light source and generate 20 ns pulses to effectively freeze the flow.

3 Results and Discussion

Time-averaged pressure distributions of the isolator and combustor are presented in Figure 2 for the different fueling conditions tested. These results were obtained by averaging the static pressure measurements recorded after the igniter shut-off and are therefore representative of the steady state operation of the combustor. For each case, the average pressure values were normalized using the heater exit stagnation pressure recorded and shown in Table 1 ($P0_{REF}$ = P0). A no-injection condition is also provided as a reference.

The results presented in Figure 2 show how with fuel injection there is a distinct pressure rise in the duct generated by combustion heat release. As expected, the amount of pressure rise scales with the amount of fuel injected and the amount of heat liberated through combustion. These pressure distributions are mainly useful however to identify the operating mode of the combustor at each fueling condition and to therefore establish the boundary between scramjet and ramjet operation. For this laboratory-scale combustor, the limit condition between these operating modes occured between a $\Phi = 0.10$ and 0.12. This is apparent from the substantial difference in static pressure at the point of injection ($x/H = 0$) between these two cases. For fueling conditions lower than a $\Phi = 0.10$, the undisturbed flow upstream of the fuel injection point and a relatively low pressure rise in the combustor are indicative of scramjet operation. Conversely, for a $\Phi = 0.12$ or higher, the flow upstream of the fuel injection point cannot be isolated from the combustion process downstream. The steep pressure rise and its propagation upstream of the location of fuel injection are characteristic of ramjet mode combustion.

Fast Fourier transforms of the dynamic pressure measurements obtained for some of the fueling conditions in Table 1 are presented in Figure 3. The frequency range of these pressure spectra was truncated at 4 KHz as no significant pressure oscillations were observed at higher frequencies. In the dual mode regime investigated between a $\Phi = 0.04$ and 0.20, the results in Figure 3 show that as the amount of fuel flow increased and the combustor goes from operating in scramjet to ramjet mode, a low amplitude broadband pressure spectrum develops. Initially for the lower two fuel injection conditions where the combustor operates in scramjet mode, the pressure spectra appears to have a wide range of low amplitude frequency components without a dominant oscillation. Near the scramjet-to-ramjet transition condition of $0.10 < \Phi < 0.12$, a distinct broadband pressure spectrum appears peaking at a frequency of 1290 Hz for a $\Phi = 0.12$. Finally for the highest two equivalence ratios where the combustor operates in ramjet mode, the magnitude of the spectral content decreases in comparison to the $\Phi = 0.12$ case but conserves its general characteristic broadband shape. A zoomed-in comparison of the pressure spectra for the lowest fueling scramjet condition and the highest fueling ramjet condition is presented in Figure 4.

A close-up view of the spectral peak at a $\Phi = 0.12$ and the pressure spectra for a $\Phi = 0.10$ and 0.14 are displayed in Figure 5. The comparison of the results for these fueling conditions demonstrates that oscillations of similar amplitude and frequency occur in the combustor when operating in scramjet and ramjet modes at an $\Phi = 0.10$ and 0.14, respectively. The comparable spectra at these two different equivalence ratios and combustion modes makes the $\Phi = 0.12$ condition especially outstanding. The ~75%

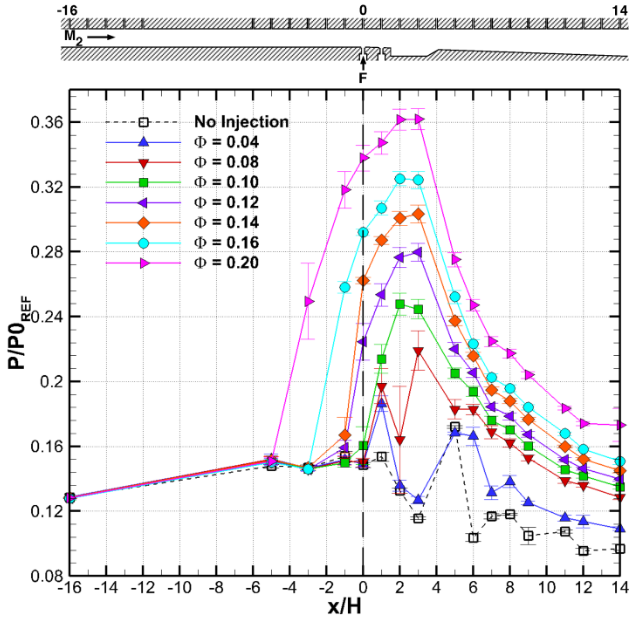

Figure 2. Time-averaged static pressure distributions through the flow path as a function of equivalence ratio.

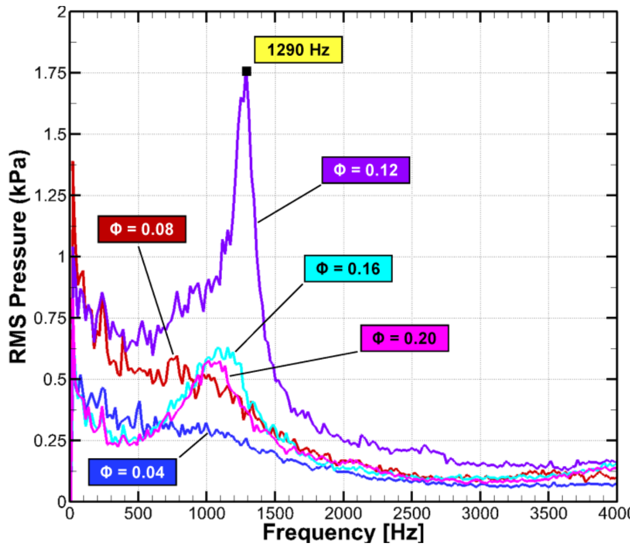

Figure 3. Pressure spectra obtained from FFT analysis of band passed-filtered dynamic pressure measurements.

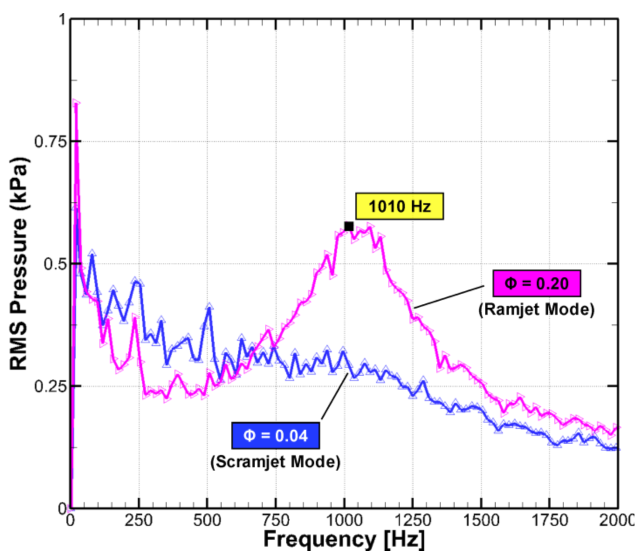

Figure 4. Close-up comparison of pressure spectra at lowest and highest fueling conditions tested.

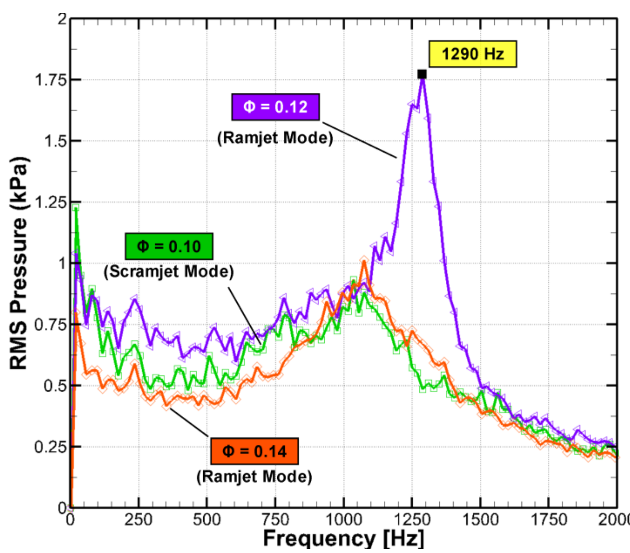

Figure 5. Close-up comparison of broadband pressure spectra for fueling conditions near transition regime.

increase in oscillation amplitude and the spectral shift from ~1050 to ~1300 Hz when compared to a Φ = 0.10 or 0.14 suggest that at a Φ = 0.12 the combustor operates in a particularly unstable ramjet mode.

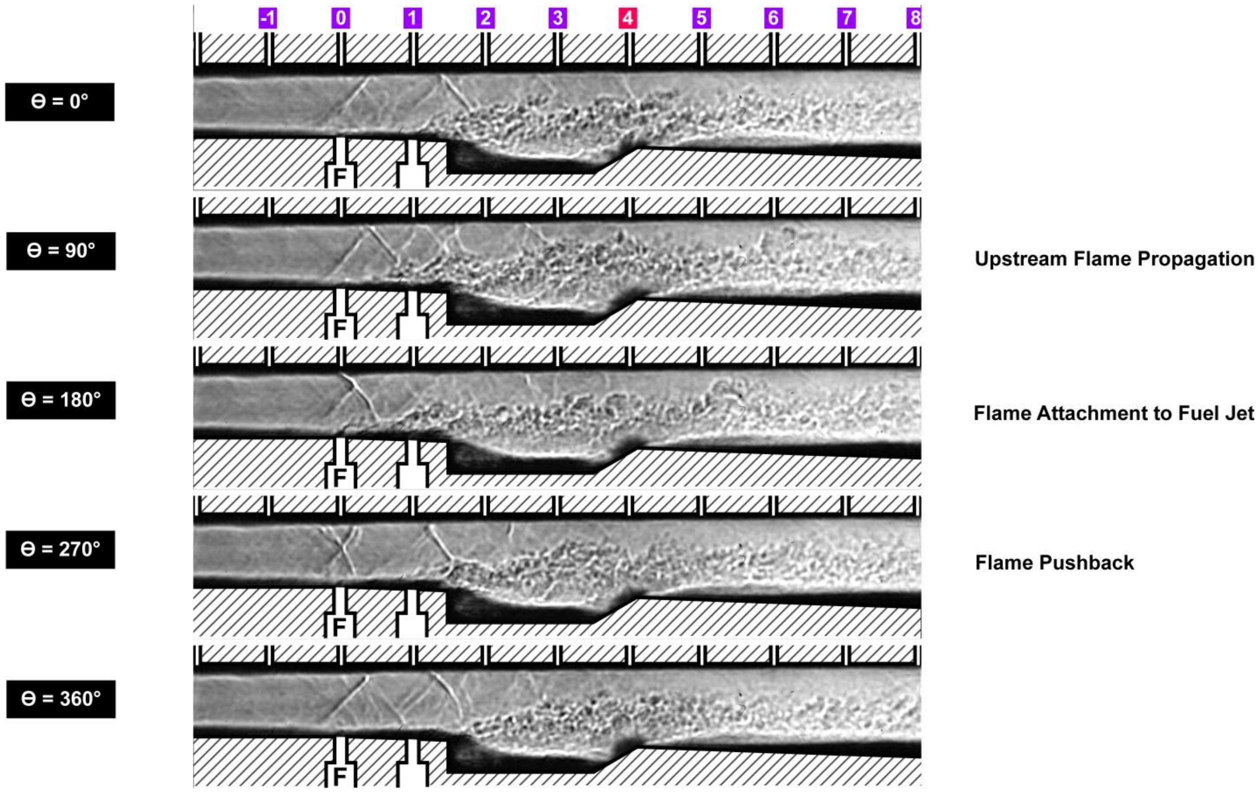

Figure 6. Selected images of a typical flame oscillation cycle for a $\Phi = 0.10$.

High-speed Schlieren sequences were analyzed to obtain insight into the potential flow physics responsible for the high dynamic content of the pressure spectra near the scramjet-ramjet transition boundary. Figure 6 contains a sequence of Schlieren images obtained from a test with a combustor equivalence ratio of 0.10. For each of these images, the flow moves left to right and the location of fuel injection is indicated by a letter "F". A close look at the position of the flame and the different shock structures that appear upstream of the fuel injection port reveal how there is a cyclic flame front motion occurring inside the combustor. Initially, the flame appears to be attached to the cavity and a jet-induced oblique shock is located just upstream of the fuel port ($\theta = 0°$). Next the flame begins to propagate upstream towards the fuel injection plane ($\theta = 90°$). Half way through the cycle, the flame reaches the injection orifice and attaches to it. The pressure rise associated with this event allows an oblique shock train to propagate upstream and interact with the upstream jet-induced shock ($\theta = 180°$). Finally, the flame detaches from the injection orifice and begins to travel back ($\theta = 270°$) until anchoring again to the cavity shear layer ($\theta = 360°$).

The cyclic flame front movements observed in the Schlieren images for a $\Phi = 0.10$ help explain the characteristic broadband pressure spectra presented in Figure 5. However, understanding what triggers these flame dynamics is also of interest, especially near the scramjet-ramjet operation boundary as seen for a $\Phi = 0.12$. Near that thermal choking condition the system is especially vulnerable to small heat release and pressure fluctuations. A slight increase in combustor pressure can be sufficient to destabilize the upstream flow and enable an upstream propagation of the flame through the wall boundary layer.

Downstream push back of the flame could be a result of the upstream propagation of a shock train and a transient local pressure increase above the fuel port. This could temporarily reduce the fuel flow rate through the unchoked orifice and force the flame front back to the cavity region.

4 Conclusions

The dual-mode regime of a laboratory scale scramjet combustor with a cavity flame holder was experimentally characterized to study the combustion dynamics associated with scramjet-to-ramjet transitions. Combustor equivalence ratios in the 0.04-0.20 range were tested using hydrogen fuel injected through a wall orifice. Static pressure distributions demonstrated that the combustor undergoes thermal choking for a combustor equivalence ratio between $0.10 < \Phi < 0.12$. Below this threshold, the combustor operated in scramjet mode featuring a pressure spectrum with a wide range of low amplitude frequency components. Around the transition threshold a well-defined and dominant pressure oscillation appeared peaking at a frequency of 1290 Hz. This outstanding ramjet operating point proved to be a especially unsteady condition that in a real system should be avoided. This behavior was correlated to upstream-downstream flame front movements visualized in a sequence of Schlieren images. Finally, for the highest two equivalence ratios above the transition threshold the amplitude and frequency of these flame oscillations subsided but the pressure spectra maintained a broadband characteristic shape centered around a frequency of 1000 Hz. Some possible explanations for the occurrence of these flame oscillations are mentioned, but further studies are required to thoroughly understand the nature of these unsteady flame oscillations.

References

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