Controlling Combustor Mode Transition in Dual-Mode Scramjet

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1 Abstract

Dual-mode scramjet combustor can be operated either in a thermally-choked combustion mode or in a supersonic combustion mode, depending on the fueling and the flight conditions. While performing direct-connect combustor mode transition experiments, we found that combustor becomes susceptible to combustion instabilities when the combustor goes through a natural mode transition process. To explore the possibility of actively triggering combustor mode transition avoiding combustion instabilities, we performed a series of spatially distributed fuel injection experiments while maintaining the total fuel flow rate constant. The experiments were performed at Mach 2 isolator conditions and with hydrogen as the main fuel, injected through a varying number of injectors via a distributed fuel injection system. Various flow visualization techniques and wall pressure measurements are employed to examine the relationship between combustor behavior and the degree of fuel distribution. The results indicate that the timing of combustor mode transition can be precisely controlled by active scheduling of fuel injection distribution. In the case of single injection, most of heat release occurs near the cavity flame-holder causing a comparatively large pressure jump and subsequently an early transition to thermal choking. In the distributed fuel injection case, heat release becomes more evenly distributed across the expanding portion of the combustor, which mitigates the flows tendency to cause thermally choking at a lower equivalence ratio. Through the use of fast-acting solenoid valves, fuel injection distribution can be modified triggering a rapid combustor mode transition without altering the total fuel flow rate. This also allows the combustor mode transition to take place on a substantially faster time scale, on the order of a few millisecond, rather than about a 500-msec time scale associated with natural mode transition process. The results demonstrate the possibility of actively controlling the combustor mode transition in a dual-mode scramjet combustor through appropriate fuel injection distribution and timing.

2 Introduction

Dual-mode scramjet combustor can be operated either in thermally-choked mode or in supersonic combustion mode, enabling air-breathing propulsion over a wide range of supersonic and hypersonic flight conditions. [1–3] The different modes are possible by adjusting the amount of heat release over the confined combustor area, which lead to drastically different combustor pressure distributions affecting the propulsion performance. [4, 5] There is a critical amount of heat release which marks the transition where the combustor flow switches from one mode to the other [1].
Fotia and Driscoll [2] found that the equivalence ratio of fuel injected as well as passive mechanisms

of heat loss to the walls affected thermal choking behavior. Aguilera and Yu [3] reported that while the combustor equivalence ratio controls mostly the transition from one mode to the other, there is also a hysteresis depending on the direction of the mode transition as well as the change in fuel flow rates.

In typical experiments, the fuel flow rates are adjusted gradually changing the total amount of heat release, until the combustor transitions into the desired mode of operation. However, it is difficult to control the timing of mode transition precisely due to many uncertainties, and the transient process itself can cause other problems such as combustion dynamics. For example, in recent experiments, large flame movements and combustion instabilities were observed when operating near the critical equivalence ratio for mode transition as shown in Fig. 1. [6] This mode transition has been characterized to be a highly unstable process with frequent mode-hopping events which affect the overall stability of the engine [3]. As such, combustion dynamics and combustion mode transition behaviors in dual-mode scramjets are still an open area of research.

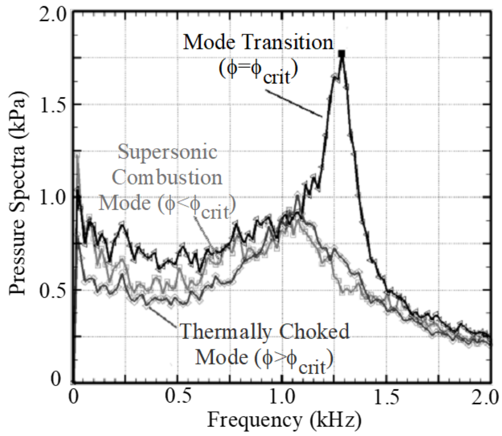

Fig. 1: Combustion dynamics associated with combustor operation near the mode transition regime [4].

Distributed fuel injection shows promise as a method of better controlling this transition between modes without any significant performance differences [7, 8]. Past studies on distributed and staged injection schemes like that of Kobayashi et al.[9] and Tomioka et al. [10, 11] have looked at the performance and thrust aspects of the different schemes, but distributed fuel injection methods can also be applied as a way of controlling the overall stability of the engine. The experiments performed by Yokev et al [7] demonstrate that a multiple fuel injection scheme can alter the pressure and heat release profile in the scramjet by controlling the flame-stabilization and heat release in the cavity.Furthermore, it is suggested that a multiple injector scheme may allow the combustor to operate in different modes of operation under the appropriate conditions.

The objectives of the present study are to investigate the effects and sensitivity of distributed fuel injection on the combustor mode transition behavior and to explore the feasibility of precisely controlling the timing of the combustor mode transition by actively scheduling the fuel distribution amount without changing the total fuel flow rate. First, fuel injectors are distributed axially along the combustor length at up to four different locations. While maintaining the same amount of total fuel flow, the combustor mode is characterized as a function of different injector combinations and redirected fuel injection profile. Then, active mode transition experiments are conducted by actively controlling fuel injection distribution.

3 Experimental Setup

Flight conditions were simulated for the experiments by using a direct-connect vitiated heat/scramjet facility. Enthalpy conditions at Mach 5 flights are simulated by vitiating the pressurized airflow, while makeup oxygen is added to the flow to maintain the same oxygen content as that of air. The details of the facility can be found in Aguilera [12]

A convergent-divergent supersonic nozzle is used to expand the vitiated flow to Mach 2 at the isolator inlet. The isolator is designed as a straight, square channel with a duct height, *H*, of 12.7 mm while the combustor incorporates a 6° constant area expansion. The combustor also incorporates a wall cavity for flame holding. There are a total of four transverse fuel injectors mounted along the upper and lower walls as shown in Fig. 2. Fuel injection is controlled using a dual-manifold system and by metering the flow rates through a combination of precision orifices and fuel pressure adjustment. Quartz windows are used in the combustor to allow for the application of various flow visualization techniques.

Sequencing and data acquisition for the system were performed using a NI CompactDAQ-9188, a NI

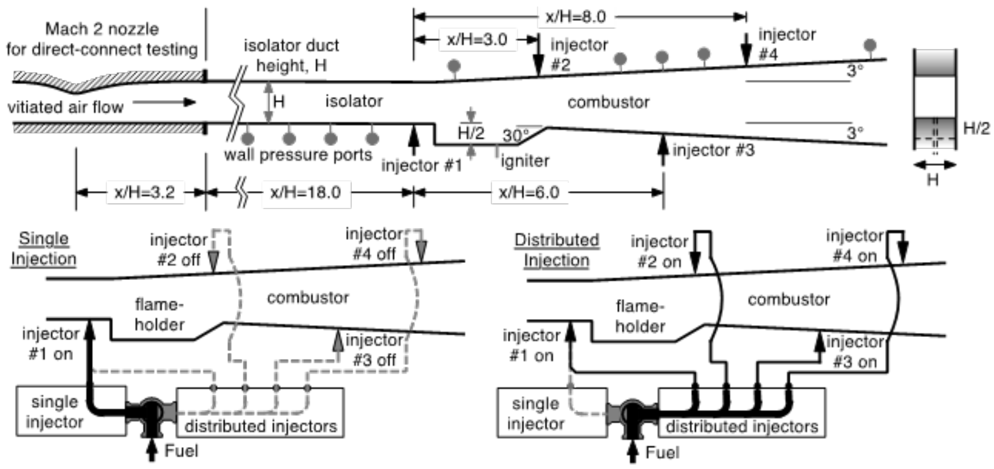

Fig. 2: Schematics of the dual-mode scramjet combustor model and actively controlled fuel injection sequencing.

CompactRIO-9022, and LabVIEW.

Table 1 tabulates three sets of combustion tests, utilizing either one, two, or four fuel injectors at the same time. For all cases, gaseous hydrogen is used as the main fuel. The first case characterizes the single injection tests. The second case characterizes the distributed injectiontests with two injectors and with four injectors. Case3 characterizes the active control tests with Case 3(a)going from single injection to distributed injection ina single test sequence and Case 3(b) going fromdistributed injection to single injection in a single testsequence. Fig. 2 also illustrates the active control sequencing used for Case 3(a) and Case 3(b) which was accomplished using fast-acting solenoid valves.

Table 1: Combustion tests performed

Case	Injection Scheme	ϕ
Case 1a	Inj. 1	0.20 ± 0.003
Case 1b	Inj. 1	0.52 ± 0.01
Case 2a	Inj. 1, 3	0.52 ± 0.01
Case 2b	Inj. 1, 2, 3, 4	0.52 ± 0.01
Case 3a	Inj. 1 to Inj. 1, 2, 3, 4	0.52 ± 0.01
Case 3b	Inj. 1, 2, 3, 4 to Inj. 1	0.52 ± 0.01

4 Results and Discussion

4.1 *Single Injection vs. Distributed Injection*

Cases 1 and 2 compare the differences between single fuel injection and distributed fuel injection. In order to better characterize the subsequent combustion tests, a baseline case of vitiated air only with no fuel injection was performed. The vitiated flow entering the isolator from the nozzle isapproximately Mach 2.0. Fig. 4 shows the normalized, static wall pressure data averaged over aperiod of 0.5s for the

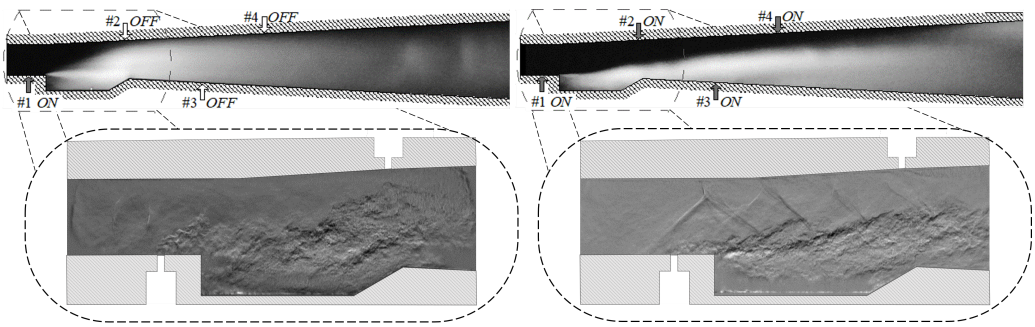

Fig. 3: Luminescence and schlieren images of the dual-mode combustor operating at thermally-choked mode (left: Case 1b) and supersonic combustion mode (right: Case 2b)

vitiated flow only (no injection), Case 1, and Case 2. The combustor begins and the isolator ends at the first injector or x/H = 0. The combustor has a six degree constant area expansion that begins at x/H=0.5, which is reflected in Fig. 4 as the baseline case pressure trace correspondingly drops as the combustor expands until x/H = 8. In the baseline case, x/H =8 marks the boundary-layer separation point in the combustor where the flow shocks up to atmospheric pressures near the combustor exit. This is evidenced by the sharp increase in pressure after this point as also shown by Fig. 4.

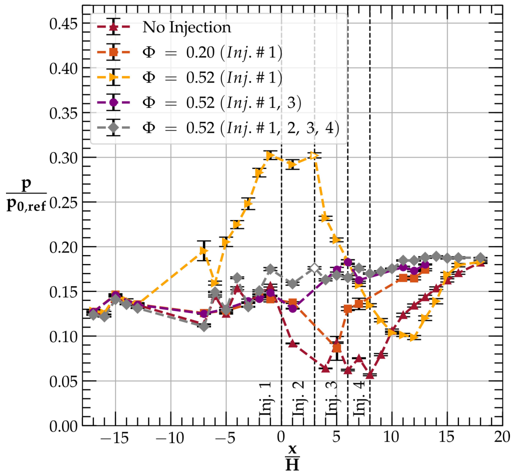

Fig. 4: Combustor and isolator wall pressure distributions for Cases 1 and 2

Case 1(a) characterizes a total fuel equivalence ratio, or ϕ, of 0.20 being injected through injector 1 only. For the distributed fuel injection cases, the first injector is maintained at an equivalence ratio of 0.20, while the remaining fuel is distributed across the other injectors equally to achieve a total ϕ of 0.52. The ϕ of 0.20 for the first injector is chosen to ensure a pilot flame is established for stable flame holding. As seen in Fig. 4, Case 1(a) has a slight pressure rise in the combustor when compared to baseline due to the modest heat release. Since the amount of heat release is relatively small, the isolator flow remains largely unaffected and the pressure in the isolator region in Case 1(a) does not deviate much from baseline case.

In Cases 1(b), 2(a) and 2(b), a total fuel equivalence ratio of 0.52 undergoes combustion in the scramjet. In Case 1(b), all fuel is injected through the first injector only, as such there is a strong pressure rise in the cavity region near the first injector, as shown by Fig. pressure, indicating the possibility of thermally choked flow. Furthermore, the pressure trace in the isolator shows a pressure rise as well in response to the large pressure rise experienced in the combustor due to the relatively large heat release. In Fig. 3, a typical, single injection case is shown with the luminescence and schlieren images confirming a stable thermally choked mode operation. The schlieren images shows a normal shock train formation while the luminescence images show the flame area capturing the full area in the cavity region. The luminescence images of Case 1(b) also show the faint traces of an oblique shock train downstream after the flow chokes in the cavity, or reaches Mach 1. In the single injection case, the flow subsequently expands back to supersonic speeds due the increasing combustor area and relatively little heat release

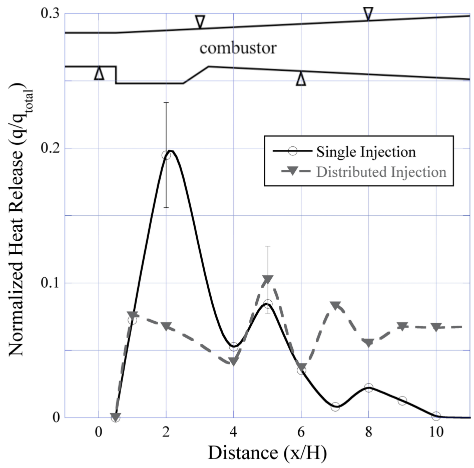

Fig. 5: Normalized heat release rate deduced from the measured experimental data and the Rayleigh Flow analysis

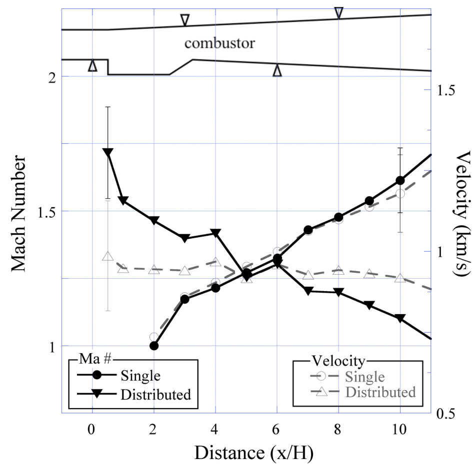

Fig. 6: Local Mach number and velocity profiles deduced from the measured experimental data and the Rayleigh analysis

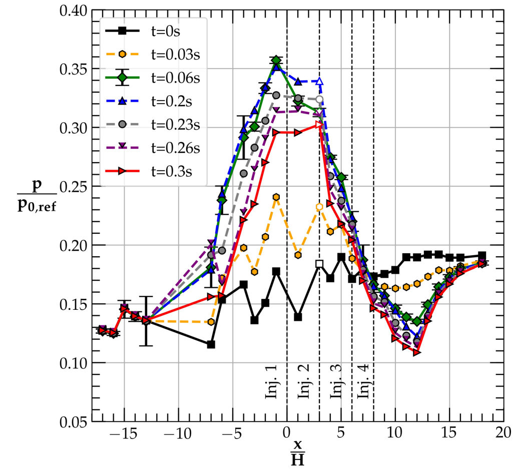

Fig. 7: Time evolution of wall pressure profile during actuated transition from supersonic to thermally choked combustion mode

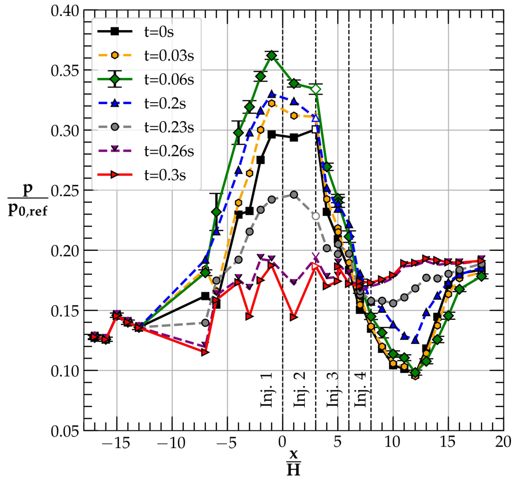

Fig. 8: Time evolution of wall pressure profile during actuated transition from thermally choked to supersonic combustion mode

downstream. The pressure data in Case 1(b) also shows evidence of boundary layer separation occurring at x/H = 12 as the flow pressure abruptly rises to match the combustor exit pressure. When compared to the baseline case, boundary layer separation in Case 1(b) occurs at a later axial distance due to larger pressure gradients present within the combustor.

Cases 3(a) and 3(b) exhibit dramatically different combustor behavior despite maintaining overall ϕ at 0.52 . As shown by Fig. 4, there is a gradual pressure rise in the combustor in both cases, which is significantly different from the abrupt, large pressure rise in the cavity region observed in Case 1(b). This indicates that a supersonic combustion event is occurring in the combustor. Moreover, in Fig. 3, a oblique shock train formation is observed in the typical, distributed fuel injection case, and thereby confirms supersonic flow as well as a stable, supersonic combustion mode.

Therefore, by changing the fuel injection distribution, different stable combustor modes were able to be achieved demonstrating the possibility of actively controlling the combustor mode transition event by appropriately scheduling fuel injection distribution.

4.2 Deduced Heat Release

By assuming one-dimensional flow, using experimental measurements, and Mach numbers known at select locations, a heat release profile in the combustor was deduced as shown in Fig. 5. Using the centerline, stagnation temperature and stagnation pressure measurements at the vitiated heater just before the supersonic nozzle with known geometry, a mass flow rate entering the isolator can be calculated. From conservation of mass, the combustor inlet conditions can be established for both Case 1(b) and Case 2(b). For the single injection case, the point of thermal choking can be assumed using previous as well as current imaging data. From the luminescence images, an intensity profile was used to calibrate the heat release profile up until the point of thermal choking in the single injection case. By using one-dimensional Rayleigh Flow with expansion, the rest of the heat release profile was deduced until the point of boundary layer separation where the one-dimensional flow assumption breaks down. Similarly for the distributed fuel injection case, one-dimensional Rayleigh Flow with expansion was also used to deduce the heat release profile.

A total heat release calculated from the known total amount of fuel injected for each case was used to normalize the heat release data in Fig. 5. As such, the integral area of the heat release distribution in both cases should be and are comparable as a similar equivalence ratio of fuel is injected in both cases. The fuel distribution scheme is shown to have a drastic effect on the heat release distribution within the combustor. In the case of single injection, there is a large amount of heat release in the more confined area of the cavity, which is more likely to cause the flow to choke. In the distributed fuel injection case, however, heat release is more gradual across the combustor and occurs at larger cross-sectional areas of the combustor which means that thermal choking can be delayed. Therefore, with distributed fuel

injection more total heat can be added before the flow chokes.
From the heat release profile, a deduced Mach number and velocity plot is obtained using Rayleigh Flow analysis as shown by Fig. 6. In the single injection case, the flow chokes at x/H = 2, the assumed point of thermal choking, and afterwards is shown in Fig. 6 to expand back to supersonic speeds as the flow encounters larger area cross-sections and there is less heat release. In the distributed injection case, the combustor entrance Mach number is shown to be supersonic and Mach number gradually decreases as more heat release occurs along the combustor length. Furthermore, the speed of sound increases in the downstream portion of the combustor which serves to drive the Mach number down.

4.3 *Active Control*

Cases 3(a) and 3(b) establishes the active control tests whereby one injection scheme switches to another in a single test sequence by actively scheduling fuel injection and controlling the fuel distribution. Fig. 7 shows the transition between distributed injection/supersonic combustion mode to single injection/thermally choked mode, while Fig. 8 shows the transition between single injection/thermally choked mode to distributed injection/supersonic combustion mode. While the wall pressure data responds rather slowly to the change in combustor mode, the characteristic time for mode transition can be inferred from the high-speed visualization images, which revealed that the characteristic time was on the order of 1 msec for mode transition.

5. Conclusions

Effects of axially distributing fuel injection on dual-mode scramjet combustor performance were investigated and the experimental results were compared against the baseline case with a single-point injection having the same total equivalence ratio. In particular, the study was focused on the possibility of controlling the combustor mode transition by actively scheduling the fuel injection location without affecting the total fuel flow rate.
Active control demonstration experiments were conducted in which fast-acting solenoid valves were used to rapidly switch the fuel injection scheme from the single-point injection to the distributed injection and the vice versa, without changing the total fuel flow rate. With the total equivalence ratio fixed at 0.52, this caused combustor mode transition to occur almost instantaneously with the switching of the injection scheme. The actual mode transition time was observed to be much shorter than the natural transition time scale.
The relatively long time scale associated with the natural mode transition process is of a concern due to the risk of establishing combustion instabilities. This approach of using distributed fuel injection scheme for active mode transition could avoid combustor operating in unstable regimes where large-amplitude combustion dynamics could trigger potentially unwanted events such as inlet unstart. Thus, the present results open up the possibility of actively controlling the combustor mode transition in a dual-mode ramjet-scramjet combustor using distributed fuel injection scheduling.

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