

ABSTRACT

Title of Dissertation: **SCRAMJET COMBUSTOR MODE TRANSITION
BY CONTROLLING FUEL INJECTION DISTRIBUTION**

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Dual-mode scramjets are able to expand the operable Mach number range of the simple scramjet through manipulation of a thermal throat. Using the thermal throat, the scramjet can operate in either thermally-choked mode or supersonic combustion mode. The transition between these two events is still not very well understood. Past research has shown natural combustor mode transition to be highly unstable and characterized by frequent mode hopping. Long timescales associated with combustor mode transition also increase the potential for combustion dynamic events to occur. Due to the high level of hysteresis present in these events, designing a way to precisely controlling mode transition timing proves to be an ongoing challenge. The present research seeks to use a distributed fuel injection method to control and better understand combustor mode transition behavior.

This study was performed using a laboratory-scale, direct-connect scramjet combustor. The facility simulated Mach 5 flight conditions using vitiation to match the enthalpy conditions necessary and to recreate typical isolator and combustor flowfields characteristic of the dual-mode

scramjet. A supersonic nozzle was employed to achieve an isolator inlet Mach number of 2.0. For the reacting flow tests, gaseous hydrogen was injected through one to four injectors using a distributed fuel injection scheme while keeping a global equivalence ratio of 0.52 constant. Various imaging diagnostics and wall pressure measurements were used to better study the relationship between combustor behavior and the number of fuel injectors. The findings revealed that combustor mode operation has a significant effect on combustor performance, as indicated by the pressure rise, axial heat release distributions, and local flowpath Mach number for these cases. The deduced heat release for the single injection case showed that most of the heat release occurs near the cavity flame-holder leading to a relatively large pressure jump causing a premature transition to thermal choking. In the case of distributed injection, heat release occurs more evenly across the expanding portion of the combustor, which prevents early transition to thermal choking. Active control of the combustor mode transition event is demonstrated through the use of a fuel injection distribution and scheduling system as well as fast-response solenoid valves. In the active control cases, the global equivalence ratio was maintained at 0.52, but using the active control system the combustor was able to bidirectionally switch between stable, thermally-choked mode and stable, scramjet mode. Furthermore, actively controlled mode transition occurs at much faster timescales than what was observed for natural mode transition. This allows for the potential to actively control on demand combustor mode transition in a real world dual-mode ramjet-scramjet combustor through appropriately scheduled fuel injection distribution.

Scramjet Combustor Mode Transition by Controlling Fuel Injection Distribution

by

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Dedication

This work is dedicated to my family and friends, without whom I would not be who I am or where I am today. My parents immigrated here with the hopes of building a better life and future for their children, and they have certainly given us the opportunities that they did not have. Thank you for always being there and making sure we always had what we needed to succeed.

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List of Abbreviations

2	Isolator Inlet
3	Combustor Inlet
ϕ	Combustor Equivalence Ratio
γ	Specific Heat Ratio
∞	Freestream Conditions
a	Speed of Sound
H	Isolator Height (0.0127 $m = 0.5$ <i>in.</i>)
M	Mach Number
t	Time
T	Static Temperature
T_0	Total Temperature
P	Static Pressure
P_0	Total Pressure
x	Axial Coordinate
2pFLDI	Two-Point Focused Laser Differential Interferometry
PLIF	Planar Laser Induced Fluorescence

Chapter 1: Introduction

1.1 Hypersonic Flight

Since the advent of hypersonic flight, around when Robert M. White flew the North American X-15 at Mach 6.7 on 22 September 1963, hypersonics has become an area of great interest and study over the years leading to advances in hypersonic vehicles and further understanding of the hypersonic regime [1]. Ramjets were considered an option for operating at hypersonic speeds but were eventually seen as impractical for speeds greater than Mach 5. With the work of Weber and MacKay [2], who compared performances of the scramjet and a hydrogen powered ramjet in Mach 4-7 regimes and claimed that the supersonic combustion ramjet or Scramjet was more ideal for speeds greater than Mach 7, the scramjet started to garner more interest [3]. Weber and MacKay [2] also identified some of the problems associated with scramjet engines such as attaining adequate mixing without strong shock losses, wall cooling, nozzle performance, and thermal choking [3]. Scramjet research has come a long way since and many improvements continue to be made and investigated.

1.2 Scramjet Development

One of the early precursors to the dual-mode scramjet is the ramjet. Ramjets are generally used in flight conditions with Mach numbers between 3-6 and mostly for supersonic flight [4]. In a ramjet, the entering freestream supersonic flow is usually compressed before entering the combustor through a system of oblique and normal shocks accomplished using the geometry of the vehicle and a converging duct [4]. Essentially, combustion occurs at subsonic speeds in the ramjet. With higher Mach numbers, combustion at subsonic speeds becomes less than ideal as the temperatures of the gases in the combustor will become very high. At high inlet Mach numbers in ramjets, not only do concerns arise regarding wall cooling, high pressures, and performance losses due to the appearance of normal shocks, but also regarding dissociation reactions due to high static temperatures in the combustor, which take away some of the chemical energy from combustion [4, 5]. As the inlet Mach number increases, the temperature of the inlet flow also increases while the temperature rise due to combustion decreases as a result of the endothermic dissociation reactions that start to occur. Eventually a point is reached where the combustion products are at a lower temperature than the entering air. The ramjet's limitation in this regard is one of the factors that drove further research into the scramjet.

In the scramjet, the combustion process occurs with supersonic flow. This mitigates the ramjet's limitation at higher Mach numbers as the flow will be at a lower static temperature in the combustor. This, however, is only ideal for a certain range of Mach numbers, as ramjets are more suited for flight between approximately Mach 3 and Mach 6. Furthermore, supersonic combustion is associated with a higher total pressure drop when compared with subsonic combustion [4, 6]. The relationship between Rayleigh heat addition and total pressure drop is characterized

by the following equation

$$\frac{dp_t}{p_t} = -\frac{\gamma Ma^2}{2} * \frac{dT_t}{T_t}, \quad (1.1)$$

where p_t and T_t represent the total pressure and total temperature, respectively. M , γ , and a represent the Mach number, ratio of specific heats, and the speed of sound, respectively. Cui et al. [6] and the technical comments of Yang et al. [7] discuss the physical implications of Equation 1.1, namely, that heat addition, or increasing total temperature, always leads to total pressure decrease. Moreover, as the combustor inlet Mach number increases, the rate of total pressure decrease increases.

1.3 Isolator

One of the ways to expand the range of Mach numbers of these engines led to the creation of the dual-mode scramjet. The geometry of a dual-mode scramjet is similar to a regular scramjet except for the inclusion of a constant area diffuser also known as an isolator [4]. Using the isolator, the dual-mode scramjet can operate in either thermally-choked mode or scramjet mode by formation and manipulation of flow structures that are influenced by the coupling of area-distribution, fuel-air mixing, and combustion [4]. The isolator also serves a second function that is to prevent inlet unstart by preventing shock trains from reaching the upstream inlet [4, 8]. In scramjet mode, when heat is added to a combustor, an adverse pressure gradient forms and moves upstream due to heat addition which if not mitigated can lead to accelerated boundary layer growth and flow separation, and this, in turn, contributes to the formation of the oblique shock train with a supersonic core flow as shown by Figure 1.1 in order to match the combustion pressure [4, 8].

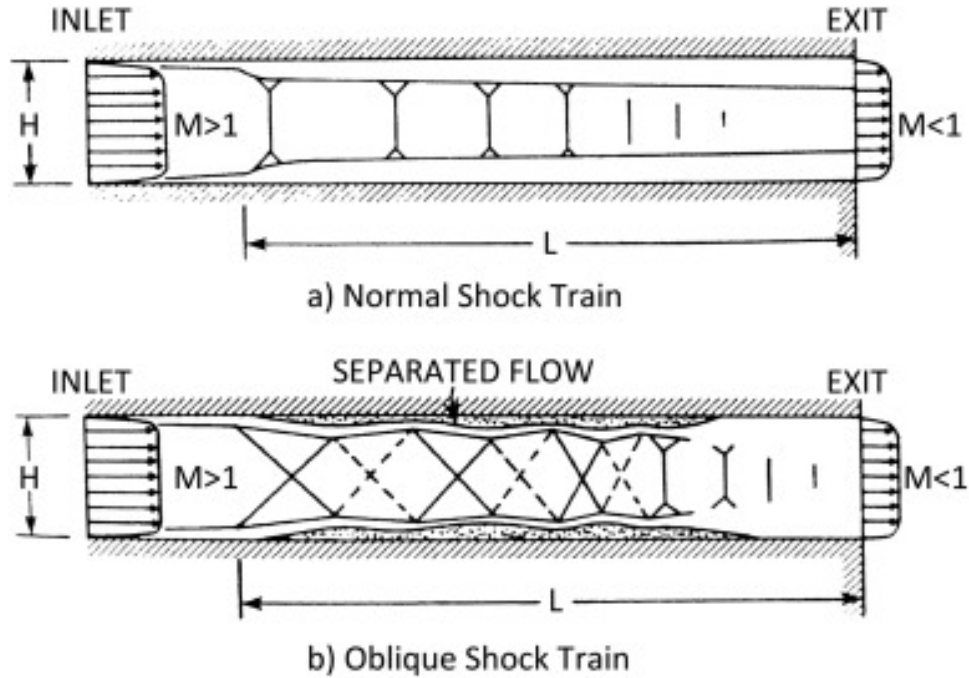


Figure 1.1: Depictions of typical isolator flow structures adapted from Pratt and Heiser [8].

In ramjet mode, the isolator is used to contain the normal shock train that results from the choked thermal throat in the combustor [8]. The principles behind the choked thermal throat can be illustrated by Rayleigh Flow, or one-dimensional heat addition in a constant area duct. As shown by Figure 1.2, when heat is added to either a supersonic or subsonic flow, the flow moves towards a choked condition. Thereby, a choked thermal throat can be created in the combustor to run in thermally-choked mode. The isolator then has to support the corresponding pressure and subsonic Mach number in the burner entry, and, in order to do this, a stable normal shock train must form within as shown in Figure 1.1 [4]. In this way, the dual-mode scramjet can expand the range of Mach numbers that a simple scramjet or ramjet can operate in.

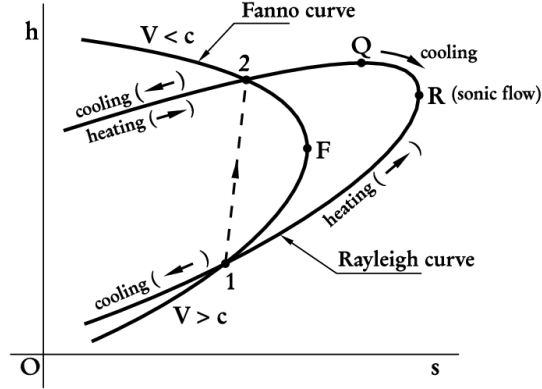


Figure 1.2: Mollier diagram depicting Rayleigh and Fanno Flow adapted from Colle [9].

1.4 Scramjet Challenges

The dual-mode scramjet, however, does inherit some of the disadvantages of the “pure” scramjet. Since combustion occurs supersonically in the scramjet, the residence times of the flow is quite fast being on the order of a millisecond [10]. Because of this, fuel mixing must occur rapidly and efficiently with minimal total pressure loss to have the most efficient combustion. Furthermore, other challenges arise such as instabilities associated with combustion mode transition, which will be further detailed in Chapter 2.

1.5 Technical Objectives

This work looks at the effect of using a distributed fuel injection scheme on combustor performance and mode transition. The motivation for this work stems from combustor dynamics and combustor mode transition behaviors in dual-mode scramjets still not being very well understood. Past studies have shown the dual-mode ramjet-scramjet to be susceptible to combustion dynamics,

especially during the ramjet-scrumjet mode transition. As such, this research investigates how distributed fuel injection may be a method to better study and control this mode transition.

Specifically, the technical objectives are:

1. To study the effect of distributed fuel injection on dual-mode ramjet-scrumjet combustor performance
 - (a) In particular, assess its effectiveness on controlling the thermal choking event
2. To better understand the physical mechanisms and the combustion dynamics associated with ramjet-scrumjet mode transition behavior
3. To demonstrate that the ramjet-scrumjet mode transition process can be controlled by distributed fuel injection and injection scheduling

Chapter 2: Combustion Stability and Performance

This chapter focuses on combustion stability in dual-mode scramjet settings. Combustor mode transition events can be a contributor to the onset of combustion dynamics in dual-mode scramjets. Past research have shown combustion dynamic events associated with combustor mode transition to be highly unstable. Fuel injection methods play a large role in maintaining overall combustion stability. Distributed injection is identified as a possible method of controlling mode transition as past studies have indicated that such an injection method has the potential to significantly alter pressure and heat release profiles within the combustor.

2.1 Combustor Mode Transition

The ramjet to scramjet transition commonly occurs as the engine accelerates and has been experimentally demonstrated before [11]. The dual-mode scramjet also has a means of transitioning back to ramjet mode from scramjet mode because of the pressure rise caused by combustion heat release as mentioned earlier. Past experiments have shown the effect of varying fuel ϕ s on the thermal choking behavior of the scramjet [12, 13, 14, 15]. As seen by Figure 2.1, the pre-combustion flow transitions from a more oblique shock train structure to a normal shock train structure as more fuel is added. Liu et al. [16] studied the effects of combustor area expansion on thermal choking behavior and noted that a balance of heat release and area relief is required

for mode transition.

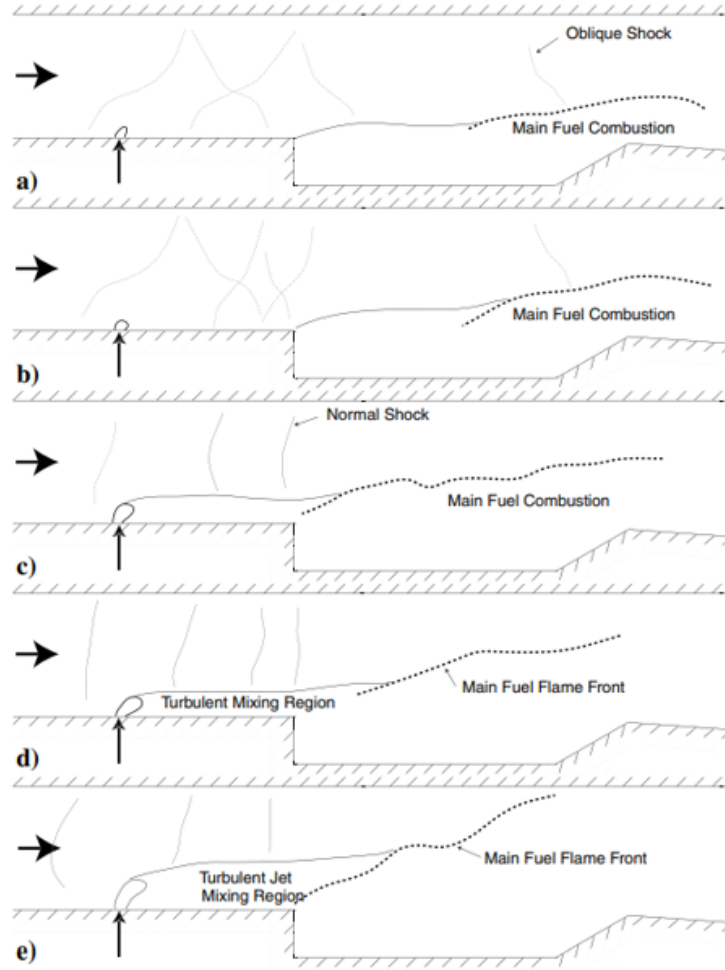


Figure 2.1: Depictions of the effect of heat release on thermal choking. Figure adapted from [17].

There are other variables that can contribute to the onset of combustor mode transition as well such as passive wall-heating, but natural mode transition was found to be highly unstable and characterized by frequent mode-hopping [12, 18]. This can lead to an unwanted combustion dynamic event and contribute to overall engine instability. The point of transition between modes is marked by a critical amount of heat addition [11]. Aguilera and Yu [12] found that although fuel ϕ plays a large role in the transition between one mode to the other, a hysteresis is exhibited

due to alteration in the fuel flow rate and the direction of mode transition. Bao et al. [19] also observed a hysteresis phenomena associated with combustor mode transition in a liquid-fueled strut-based scramjet combustor. In typical test runs, fuel flow rates are changed in such a way that the integral amount of heat release within the combustor also changes slowly and steadily leading to an eventual transition into the desired mode of operation. Precisely controlling the mode transition timing, however, is not trivial due to the number of uncertainties present and the aforementioned possibility of combustion dynamic events occurring. For instance, in recent studies, large flame oscillations and combustion dynamics events were seen during operation close to the critical ϕ needed for mode transition as seen in Figures 2.2 and 2.3 [20, 21]. Figure 2.2 depicts large flame oscillation near the critical ϕ . The physical mechanisms of this transition between modes as well as associated combustion dynamic events are still open areas of research [12, 17].

2.2 Transverse Fuel Injection

Due to the low residency times present in scramjet flow, mixing consideration become critical when developing the engine. As such, multiple different fuel injection configurations, such as strut, ramp, and transverse injectors, have been studied over the years in efforts to improve and achieve more stable combustion [22]. Furthermore, the transverse fuel injection scheme has been found to be a strong candidate as a fuel supply method in high-speed scramjet applications [22]. Transverse fuel injection is advantageous due to the flow structures it produces, which are conducive to better fuel-air mixing and cross-flow penetration with the trade-off being large pressure losses. The different flow structures present in a typical, underexpanded transverse

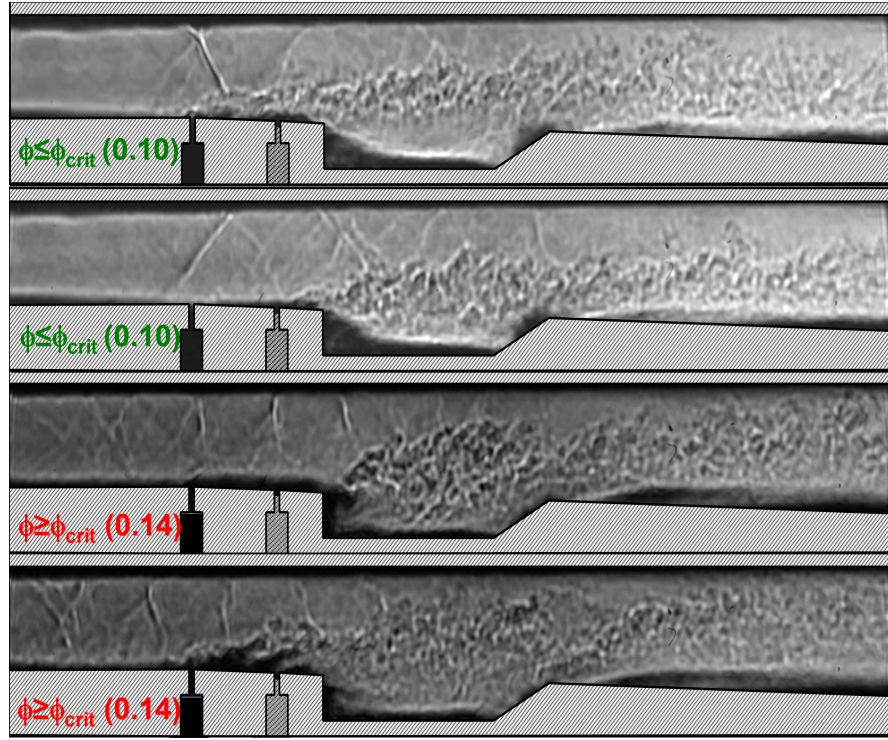


Figure 2.2: Flame oscillation near thermal choking limit. Figure adapted from [21].

fuel injection flowfield is shown in Figure 2.4. A strong three-dimensional bow shock structure appears upstream of the injector opening leading to boundary layer separation. This allows for subsonic mixing to occur between the boundary layer and fuel providing the potential for flame-holding [23]. Counter-rotating vortex pairs also form downstream of the injector which aid in freestream air entrainment and allow for mixing on the molecular level, and thereby, increasing combustion efficiency. Erdem and Kontis [24] found, through a combination of computational simulations and experiments, that increases in jet pressure ratios lead to lengthening of notable upstream and downstream flow structures and that for three-dimensional jet interactions, jet penetration is non-linearly related to momentum flux.

There has been much study into different ways to optimize the transverse injection design.

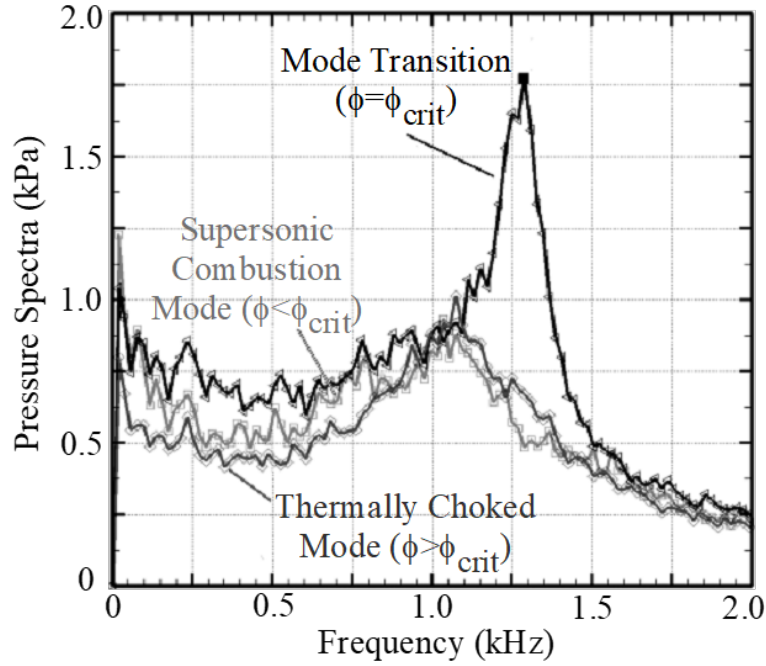


Figure 2.3: Combustion instability event present during combustor operation around the mode transition region. Figure adapted from [12].

Wang et al. [26] performed simulations on elliptic and circular injectors and found that while the shock structures formed in the elliptic injector cases maintained coherency longer, circular injectors reached higher penetration in the cross-flow. Multiple transverse injection configurations were also considered, which introduced different flow structures as shown in Figure 2.6. Lee [27] performed a numerical study on dual transverse injection and found that the distance between the injectors can be optimized to enhance mixing and penetration, and this optimum distance was related to the momentum of the fuel jets. Lee [28] also numerically studied the combustion characteristics of a dual transverse injection system and found increases in burning rates during combustion and taller flame heights. Lee [28] also found, however, larger stagnation pressure penalties when compared to single injection. Landsberg et. al [29] performed a numerical study with two hydrogen injectors at different spacings between the injectors and found significant

performance benefits when compared to a singular injector configuration.

2.3 Distributed Fuel Injection

A distributed injection scheme shows promise as a potential solution to the problems posed by combustor mode transition while maintaining combustor performance and combustion efficiency. Past research on using a distributed fuel injection scheme has shown it to have the potential to offer better control of the transition between modes without any significant performance differences [30, 31]. Previous studies on distributed and staged fuel injection methods such as Kobayashi et al. [32] and Tomioka et al. [33, 34] have focused on the performance and thrust characteristics of the different schemes. Moreover, a study performed by Kay and Guile [35] noted that using distributed injectors allow for higher combustor efficiency. The study conducted by Yokev et al. [30] found that a multiple fuel injection scheme can significantly change the pressure and heat release trace within the combustor by modulating the flame stabilization and heat release in the cavity. Moreover, the study also indicates that a multi-injector scheme may give the combustor more flexibility to perform in different modes of operation under the right conditions. Therefore, using a distributed fuel injection scheme shows promise as a method of controlling combustor mode transition.

2.4 Summary

Combustion mode transition is still an active area of research and is important in preventing unwanted combustion dynamic events during dual-mode scramjet operation. The combustion mode transition involves significant hysteresis and as such designing a precise method of controlling

this event proves a significant challenge. Distributed fuel injection has the potential of stably switching between different modes of combustion. Past research on multiple injectors has shown better mixing enhancing and, in some cases, better performance when compared to single injection. Specifically, past experimental distributed fuel injection studies have looked at the effect of distributed fuel injection on performance as well as flame-stabilization. Past studies has indicated the possibility of operating in different modes using a distributed fueling system, but a definitive method of using distributed injection to switch between modes is still an open area of research. The research performed here seeks to offer an active control of mode transition using a system of distributed fuel injection and fuel injection scheduling while also further elucidating the combustor mode transition phenomena.

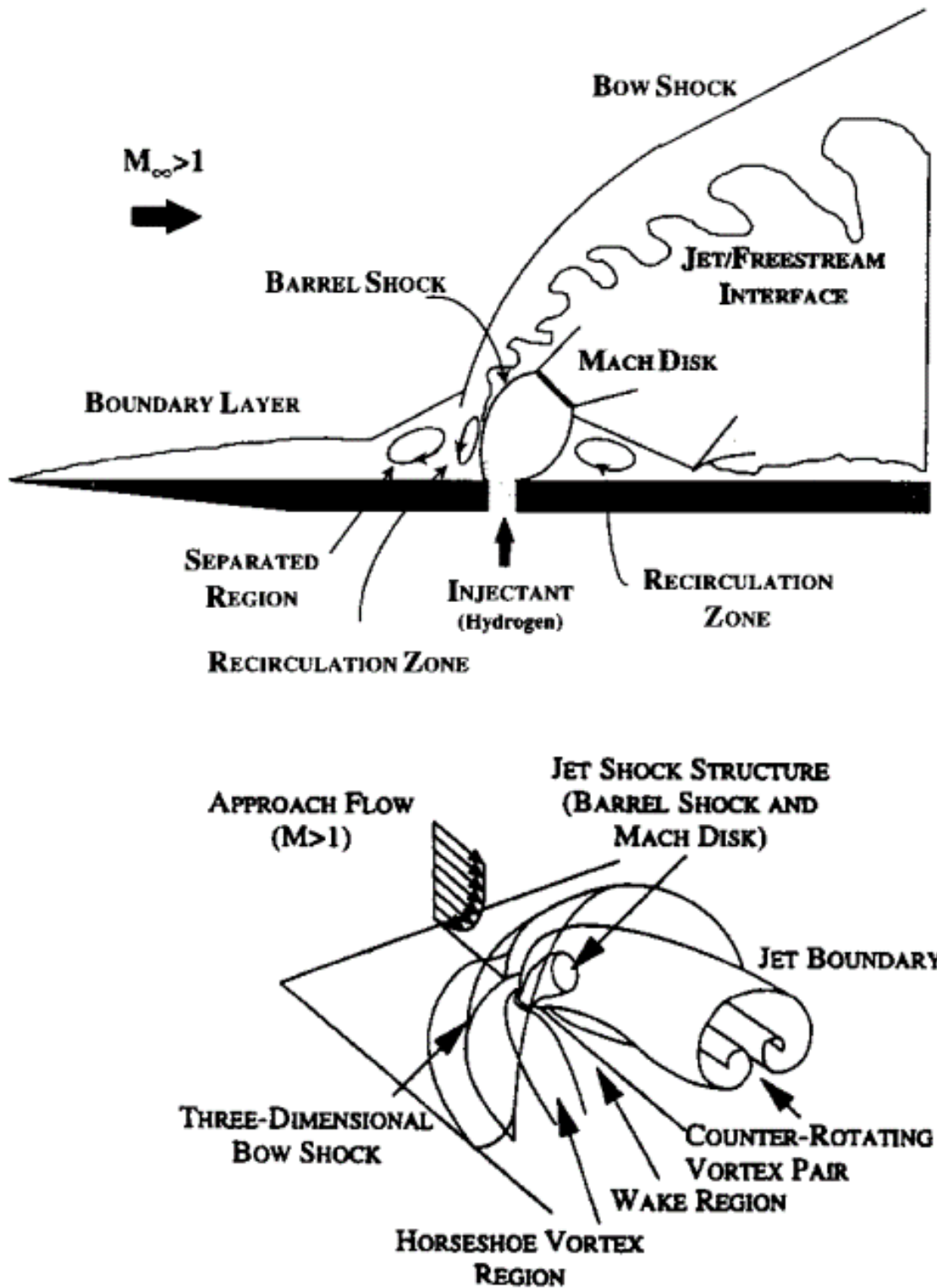


Figure 2.4: Schematic of flow structures formed during supersonic transverse injection adapted from [22, 23, 25].

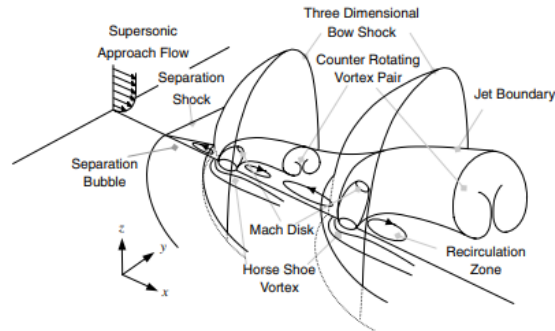


Figure 2.5: Schematic of flow structures formed during dual transverse injection adapted from [27].

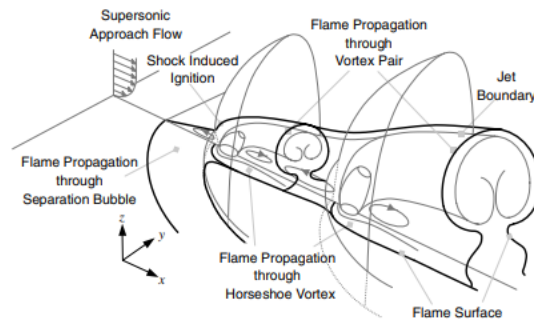


Figure 2.6: Schematic of flow structures formed and flame propagation after ignition during dual transverse injection adapted from [28].

Chapter 3: Experimental Setup and Diagnostics

A series of reacting flow tests were conducted to investigate the effect of a distributed fuel injection scheme on combustor performance and mode transition. This section covers the experimental setup as well as the diagnostic techniques used for this purpose.

3.1 Direct-Connect Vitiated Heater Facility

Flight conditions are simulated for the experiments by using a direct-connect vitiated heater. Using the vitiated heater, to achieve the flight condition desired, enthalpy is matched by raising vitiated air temperature. High pressure air is sent to the facility using an Atlas Copco GA 75 Type compressor in conjunction with a Hankison HPRP 400 - 460 dryer to remove moisture from the flow. The vitiated facility builds off of the work of Aguilera [36] as shown in Figure 3.1. The incoming flow rate of the high pressure air is metered using a 10.16 *mm* (0.4 *in.*) orifice. Past the orifice, the flow encounters an expansion joint which serves to ease expected structural stresses due to thermal loading, a blow out port designed to mitigate any sort of flame blowback event, and an expansion coupler used to increase the flow path from a 52.5 *mm* (2.067 *in.*) to a 77.9 *mm* (3.068 *in.*) diameter circular section. The vitiated heater used gaseous hydrogen fuel to raise the temperature of the flow.

Propulsion Research Lab
**Direct-Connect Vitiated Air
 Scramjet Testing Facility**

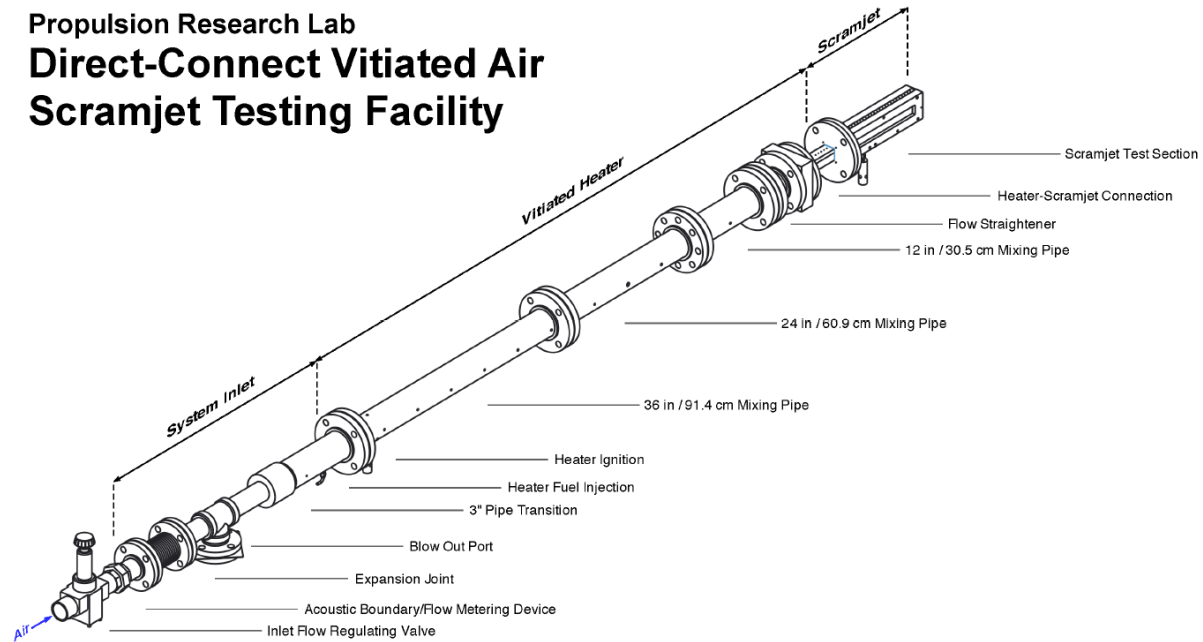


Figure 3.1: Schematic of vitiated heater facility adapted from [36] showing the inlet, vitiated heater, and scramjet portions of the rig.

The heating mechanisms of the vitiated heater is modeled after a standard gas turbine combustor. A liner cone is employed, as shown in Figure 3.2 to provide adequate fuel-air mixing before ignition which is carried out using a C_2H_4/O_2 igniter placed downstream of the cone.

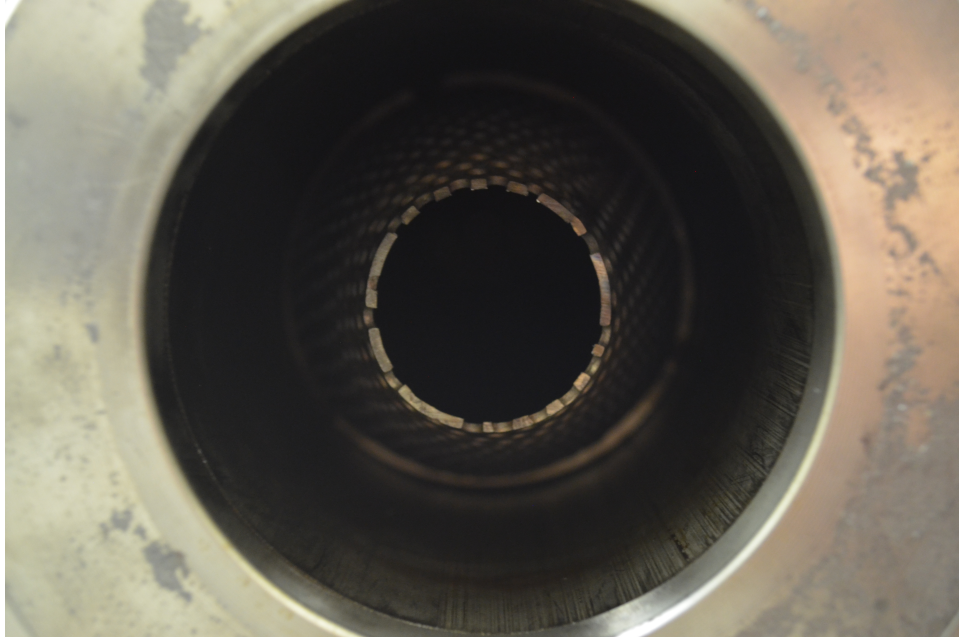


Figure 3.2: Liner cone inside the vitiated heater facility.

The igniter used an Autolite Copper Core Spark Plug powered by an AC Delco D585 ignition coil. Downstream of the igniter, the hydrogen flame passes through three directly-connected pipes which allows for sufficient mixing of the combustion products and replenishment oxygen before entering a 304 stainless steel flow straightener. Afterwards, the flow reaches the machined supersonic, Mach 2 nozzle. Stagnation pressure and stagnation temperature measurements are taken just before the half-nozzle using a Setra 206 transducer and a K-type thermocouple respectively.

Gaseous fuel and air delivery for the facility are accomplished using gas bottles and a gas

line system. A total of eight gas lines were used for the experiments. For the heater portion of the facility, one fuel line is reserved for hydrogen and two gas lines are reserved for oxygen and replenishment oxygen for the vitiation process. For the scramjet, two gas lines are used to supply the main fuel. The remaining three lines are used to provide gaseous oxygen, ethylene, and nitrogen for the igniters in both the scramjet and the heater. Gas tanks are placed behind 1/4 turn valves which allows for manual shut off in case of emergency. After the 1/4 turn valves, the gas flow encounters a 24V DC solenoid valve, a check valve to prevent any backflow, a 204 Setra pressure transducer, and a flow metering orifice.

Figure 3.3 shows a CAD drawing of the isolator/scramjet portion of the facility. The isolator duct height, H , is 12.7 mm (0.5 in.). There are a total of four injectors and one igniter. Quartz windows are used as the combustor side walls, which allow for optical access to the flow. The combustor exits immediately to atmosphere. Various wall pressure taps are located along the top and bottom surfaces of the combustor which allow for static wall pressure measurements to be obtained. Figure 3.3 also depicts the dual-manifold system that allows for control of the fuel being distributed across the multiple injectors. Each manifold is located downstream of a 24V DC solenoid valve and a Setra pressure transducer. The manifold has 4 ports that can either be linked to the fuel injectors or capped. An orifice is placed just before the fuel injection location to control the fuel flow rate.

Figure 3.4 shows the dimensions of the isolator and scramjet combustor. The cavity dimensions are modeled after previous research [36, 37]. The igniter orifice, however, is located within the cavity and is $1.5H$ from the start of the cavity dump plane. The combustor has 6 degrees of expansion which begins at the cavity dump plane.

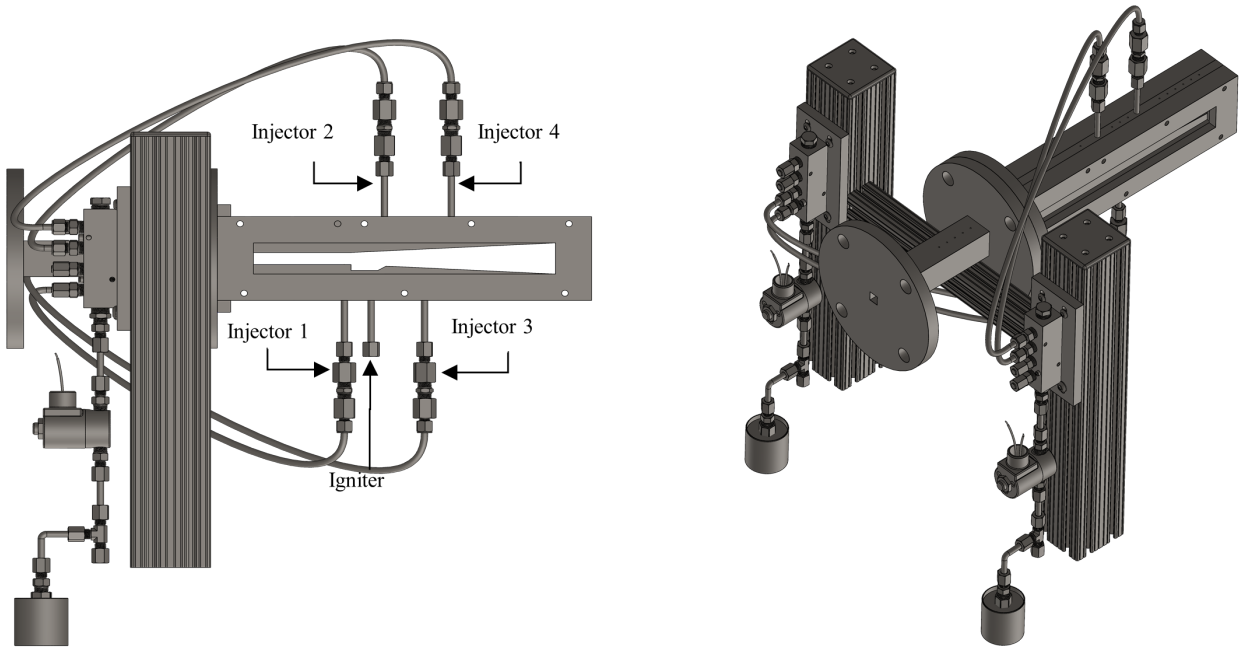


Figure 3.3: CAD drawing of fuel management system and combustor.

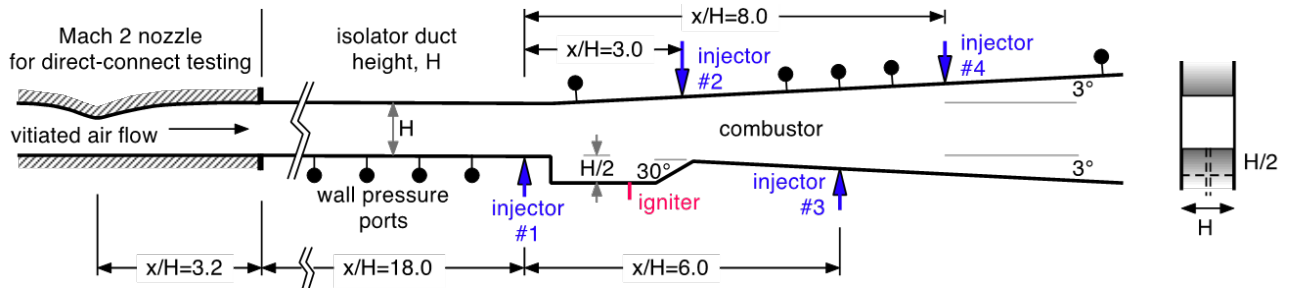


Figure 3.4: Dual-Mode scramjet schematic and dimensions.

3.2 Test Conditions

Table 3.1 shows the typical vitiated heater conditions ran for all cases. Using Cantera [38] and the vitiated heater fueling conditions, the vitiated air properties are simulated. A 21% mole

fraction of oxygen is maintained using oxygen replenishment to simulate air. The properties shown in Table 3.1 were attained using Cantera and assumes complete, adiabatic combustion at constant pressure.

Table 3.1: Typical Vitiated Heater Conditions.

V.H. Flow Rate (kg/s)	0.48-0.51
$T_0(K)$	1305-1310
$P_0(kPa)$	517-529
X_{O_2}	0.211
X_{N_2}	0.518
X_{H_2O}	0.265
$R (J/Kg \cdot K)$	315-318
γ	1.285-1.292

As shown by Table 3.2, three main cases of combustion tests are ran with gaseous hydrogen as the fuel of choice. For all cases, an ethylene/oxygen mixture igniter is used to ensure proper ignition/flame-holding, and data is obtained after igniter shut-off. Case 1 is composed of the single injection tests where fuel is sent through the first injector only. The second case is made up of the distributed injection tests with two injectors (injectors 1 and 3 from Figure 3.4) and with four injectors (injectors 1,2,3 and 4 from Figure 3.4). Case 3 demonstrates the active control tests. Case 3(a) depicts going from single injection to distributed injection in a single test sequence, and Case 3(b) depicts transitioning from distributed injection to single injection in a single test run.

Table 3.2: Combustion tests ran.

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

3.3 Test Sequencing

During a typical test run, the quarter turn valves are turned open and a NI CompactRIO-9022 is used to trigger the solenoids to commence fuel/oxidizer injection. Figure 3.5 depicts a typical test sequence for a vitiated heater only test. Pressures for each relevant gas line is plotted as a function of time. Typical test runs are 7s long. At $t = 0s$, the igniter spark is turned on. At $t = 1s$, gaseous ethylene and oxygen are injected through the vitiated heater igniter and ignited. The vitiated heater igniter runs for 2s and stops at $t = 3s$. The main hydrogen fuel and oxygen replenishment for the vitiated heater commences at $t = 2s$ and continues until the end of the test at $t = 7s$.

For typical distributed injection combustion tests, as shown in Figure 3.6, fuel is injected after $t = 3s$ through both injector 1 and injector 2, 3, and 4 and stays on until $t = 7s$. The igniter in the scramjet is turned on from $t = 2.5s$ to $t = 4s$. All fuel injection is turned off at $t = 7s$.

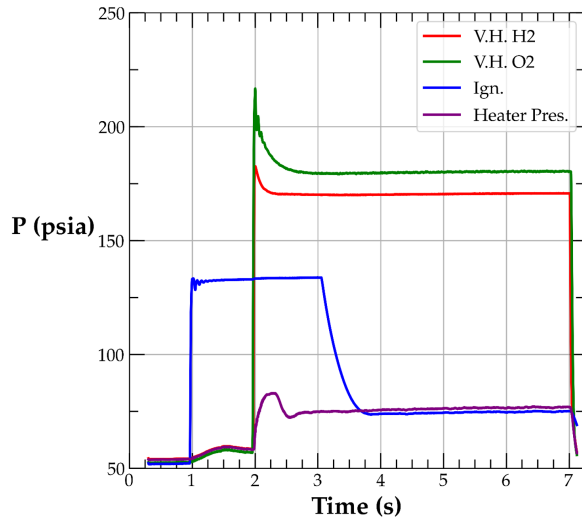


Figure 3.5: Vitiating heater fuel/oxidizer gas pressure sequencing for a typical test run.

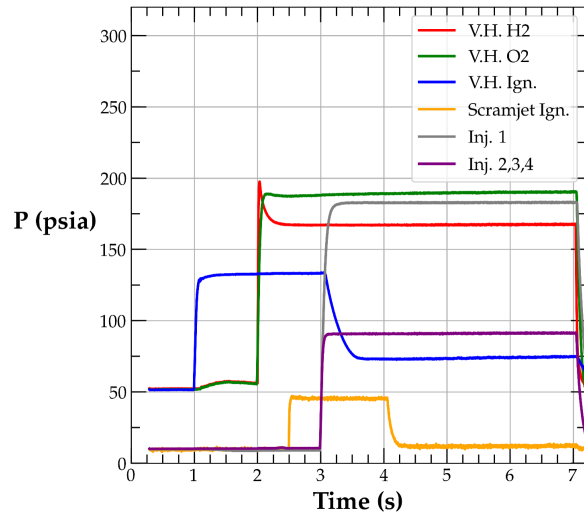


Figure 3.6: Fuel/oxidizer gas pressure sequencing for a typical combustion test run.

Figure 3.7 shows the active control sequencing used for Case 3(a) and Case 3(b) which are designed using fast-acting solenoid valves. Figure 3.8 depicts the typical pressure trace of an active control test with $t = 0s$ being when the second injection scheme turns on. The sequencing is designed so that the first injection scheme turns off $0.2s$ after $t = 0s$. In the case of Figure 3.8, the sequence goes from single injection to distributed injection. The active control tests were designed conservatively with an overlap between the two injection schemes to ensure stable flameholding while avoiding any sort of flame blow-off event.

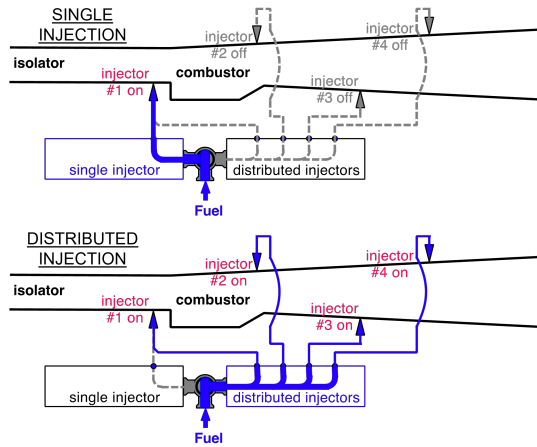


Figure 3.7: A diagram of the active control sequencing.

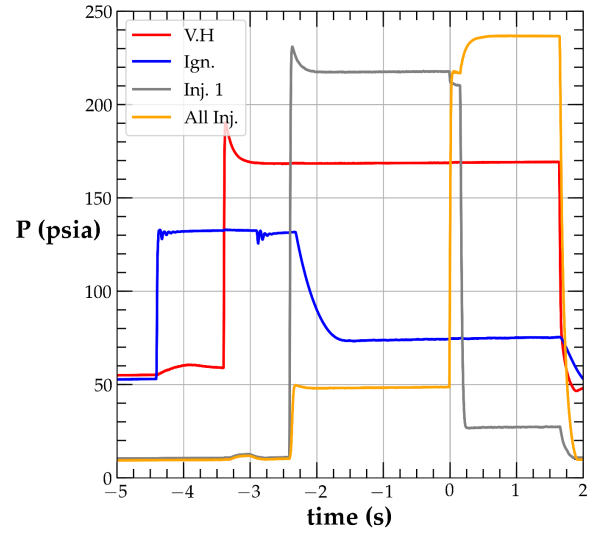


Figure 3.8: Active control test sequencing plot with timing shown using gas line pressure signatures.

3.4 Diagnostic Methods

For the scramjet reacting flow experiments, static pressure measurements were taken and various flow diagnostic techniques were applied. In order to characterize the reacting flow, static wall pressure data is collected in conjunction with schlieren imaging and broadband luminescence images. The high-speed reacting flow are also characterized by a 2-point focused laser differential

interferometry technique. These techniques and methods will be further discussed in the following sections.

3.4.1 Pressure Measurements

Pressure measurements are taken along select location of the upper and lower walls of the scramjet isolator and combustor flow path. They served to get a sense of the effects of heat addition in the combustor and also to better elucidate the combustor's mode of operation, i.e. scramjet mode or thermally-choked mode. Pressure data is measured using a Scanivalve DSA-3217 Digital Sensor Array. The module houses 16 pneumatically triggered temperature adjusted, piezoresistive pressure sensors. Using Scanivalve's DSALink4 software and a desktop PC to communicate with the module via TCP/IP and UDP, pressure measurements can be obtained and outputted as a CSV file for post-processing. A zero offset calibration was performed before each test run using the software and the module's own internal calibration valve to account for any zero drift issues due to using piezoresistive sensors.

3.4.2 Visualization Techniques

The Schlieren visualization technique relies on density gradients present in fluid flow. The schlieren technique for gases builds upon the fact that a linear relationship exists between the index of refraction, n , and density as shown in the Gladstone-Dale relationship [39]:

$$n - 1 = k\rho \quad (3.1)$$

Using the relation shown in Eq. 3.1, a comparison can be shown between the angular ray

deflection caused by refractive index gradients in the flow, whose relationship is shown in Eq. 3.2, and the density gradient [39]. Therefore, schlieren images form where changes in density appear and show up as differing levels of contrast or intensity:

$$\epsilon_y = \frac{1}{n} * \int \frac{\partial n}{\partial y} \partial z \quad (3.2)$$

For the cases tested in this experiment, two different types of schlieren setups are used: a Z-type setup and an in-line setup. For both configurations, a CAVILUX Smart System pulsed diode laser light source and a Phantom V2512 camera are used. For the Z-type setup, two 25.4 cm (10 in.) mirrors are used with a f-number of 8 to get an overall schlieren image of the whole combustor viewing area. For the closer viewing area images an in-line setup is used with 7.62 cm (3 in.) lenses with an f-number of 2.

Broadband luminescence images are also attained to complement the schlieren images using a Nikon D5100 and a Phantom V2512.

3.4.3 2-Point Focused Laser Differential Interferometry

Two-point focused laser differential interferometry (2pFLDI) is a laser-based technique that relies on turbulent structures present in the flow. Researchers at the University of Maryland, Ceruzzi et al. [40, 41], have developed a new application of the technique to obtain point-based velocity measurements. The technique works on the principle that at sufficiently small enough length scales, the turbulent structures present in the flow can effectively be considered to be frozen and moving with a certain characteristic velocity. This technique can be used to measure density fluctuations as well as disturbance velocities at the focal region of interest where the

signal is most sensitive. In a typical setup, as shown in Figure 3.9, the beams are focused down to essentially two pairs of points. Each pair measures a density fluctuation and outputs a signal which a photodiode captures. From the cross-correlation between the signals, a characteristic time the turbulent structure takes to travel between the two pairs is determined and knowing the distance between the two pairs, a velocity can be calculated. Figure 3.10 shows the 2pFLDI setup in the scramjet facility.

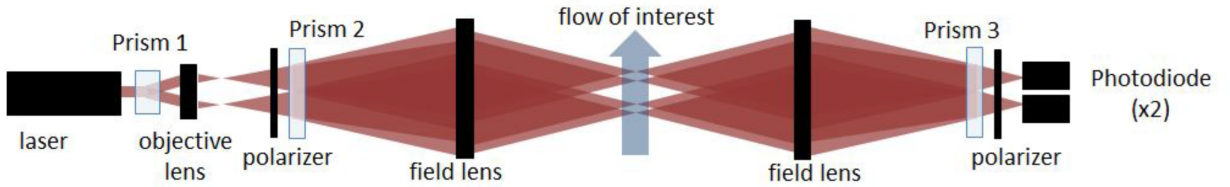


Figure 3.9: Schematic of 2pFLDI setup adapted from [40].

For the experiments done, the 2pFLDI setup is ran at sampling frequency of 62.5 MHz. The data is post-processed using Matlab. The distance between points in each pair, or Δx_1 , in Figure 3.11, is $47 \mu m$. The distance between each pair of points, or Δx_2 , in Figure 3.11, is $168 \mu m$.

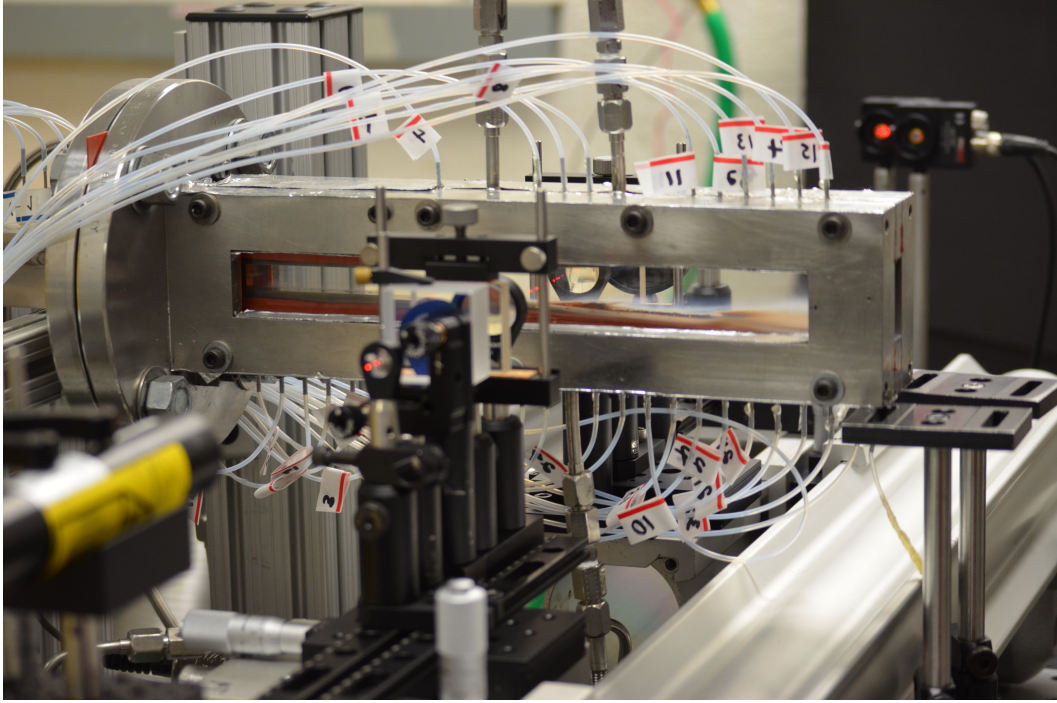


Figure 3.10: Image of the 2pFLDI setup in APRL's Dual-Mode Scramjet test rig.

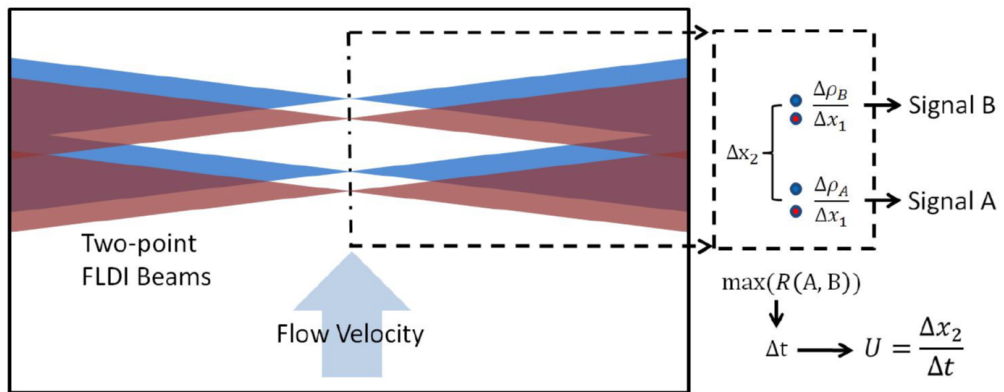


Figure 3.11: Close-up of schematic of 2pFLDI setup, adapted from [40], depicting the FLDI laser beams being focused down to four points to attain velocity measurements.

Chapter 4: Baseline and Ignition Characteristics

This chapter characterizes the baseline cases where the vitiated heater only is ran with no fuel injection in the combustor and the case where fuel is injected through the first injector only. The scramjet ignition process is also detailed in this chapter. The baseline case provides a measure of comparison for the subsequent distributed injection combustion tests. The ignition process and the flameholding mechanisms for the combustion tests are also discussed.

4.1 Baseline

The baseline case established the flight conditions that would be simulated for the experiments. For the purposes of this experiment, a temperature of approximately 1300 K is attained to simulate a flight Mach Number of 5 at an altitude of 18.5 km. Figure 4.1 shows the temperature time trace in the vitiated heater. Temperature is measured using a K-type thermocouple in the centerline of the flow at the heater exit and before the supersonic nozzle. This along with the pressure measured at the heater exit are taken to be the stagnation properties of the flow entering the isolator/scramjet. Past temperature studies of the vitiated heater facility, shown in Figure 4.2, show the flow to be parabolic in nature as would be expected in pipe flow and the maximum temperature to be located at the center of the flow.

The static pressure measurements in the baseline case is shown in Figure 4.3. The static

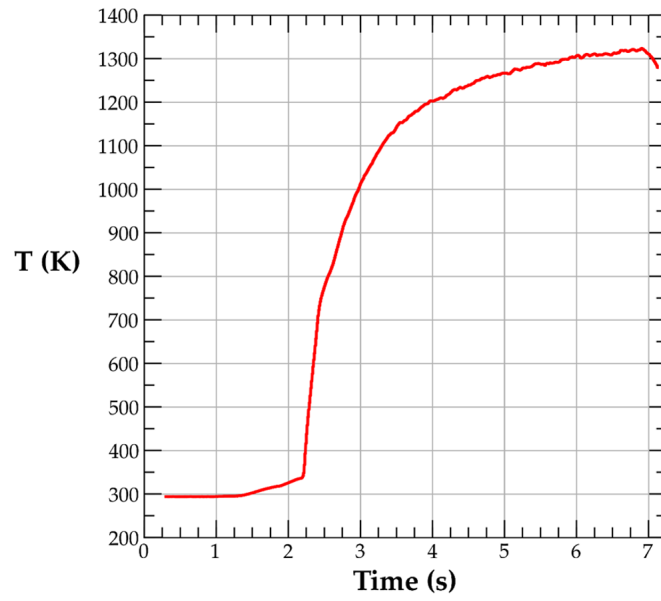


Figure 4.1: Temperature profile of the vitiated flow.

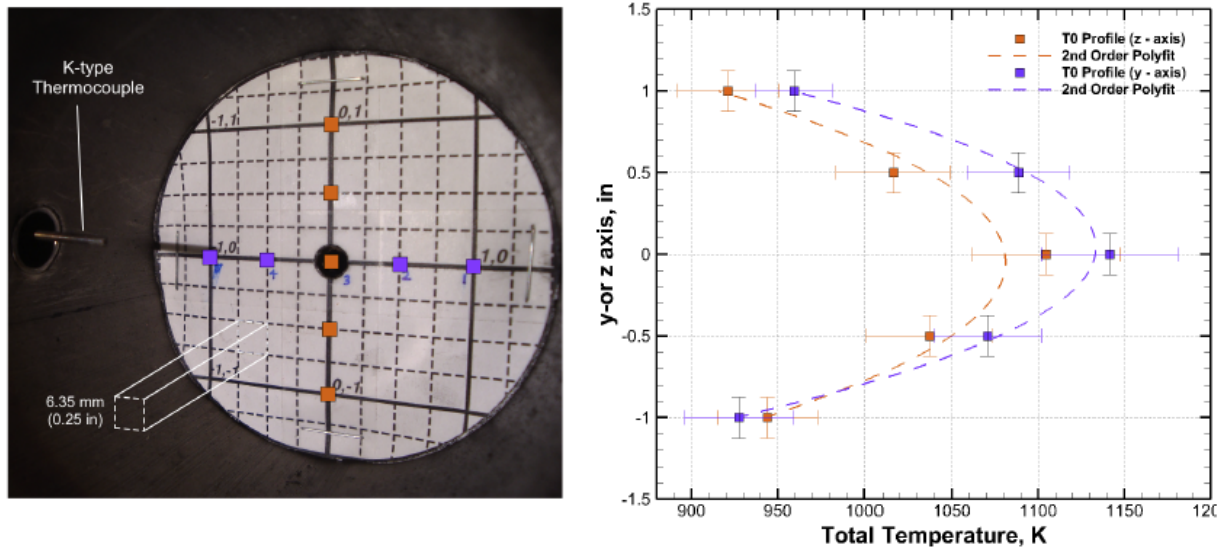


Figure 4.2: Past multi-axial temperature profile of the flow in the vitiated heater facility adapted from [36].

pressure is normalized by the reference stagnation pressure measured at the heater exit. The measured pressure data is compared to an ideal, quasi one-dimensional isentropic analysis where pressure change occurs only due to area change. In reality, there are certain entropy-generating mechanisms present in the scramjet which cause some deviation from this ideal situation. In the isolator portion of the combustor (before $x/H = 0$), a shock train forms and there are modest pressure fluctuations as a result. Overall, the baseline static wall pressure data does not deviate too significantly from the ideal analysis except at $x/H = 8$ where boundary layer separation occurs as the flow shocks up to match the atmospheric pressure at the combustor exit. By assuming one-dimensional flow, Mach number information in the isolator and combustor is able to be obtained using the measured pressure data as depicted in Figure 4.4.

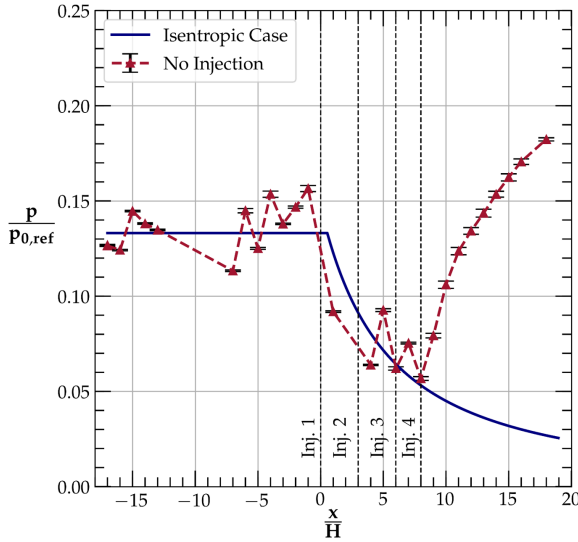


Figure 4.3: Combustor and isolator wall pressure distributions for the no injection case.

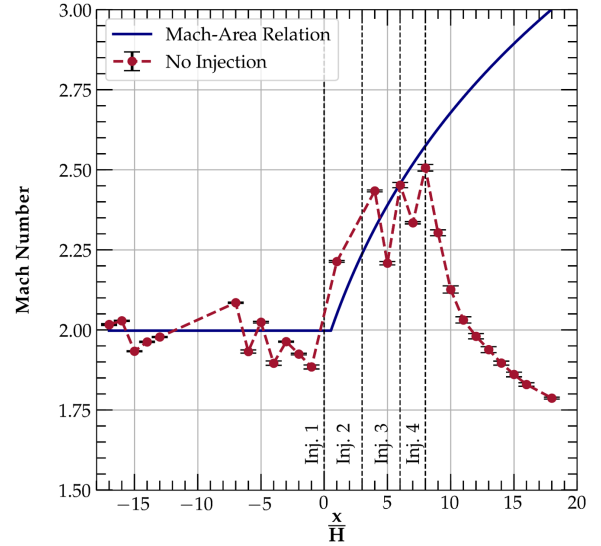


Figure 4.4: Combustor and isolator Mach number distributions for the no injection case.

This is accomplished by manipulating the known isentropic relations [42] to solve for local Mach number. The flow entering the isolator after exiting the supersonic nozzle is expected to be Mach 2. In Figure 4.4, the Mach Number starts to increase drastically in the combustor due

to area expansion, but drastically decreases at the point of boundary layer separation at $x/H = 8$.

4.2 Scramjet Ignition Characteristics

The igniter in the scramjet combustor is located within the cavity and is ran with a stoichiometric mixture of ethylene and oxygen gas. Although the total temperature measured for the vitiated flow is above the auto-ignition temperature of hydrogen (~ 860 K) [43], injected fuel may not penetrate far enough into the hot, core flow to reach the temperatures necessary to reach the auto-ignition condition. Instead, in order to ensure consistent and stable ignition, an spark-powered igniter was used. The main fuel is added through the appropriate injectors in each case 0.5 s after the igniter is turned on, and the igniter remains on until stable flame holding occurs at which point the igniter is turned off. Data for the experimental cases are collected 0.5s after the igniter shuts off and stable flame holding is achieved. This is to ensure that the igniter's combustion products are not present in the flow when collecting data. Figure 4.5 shows the ignition event in the combustor through a series of schlieren images before any fuel injection occurs through the injectors.

Past studies on scramjet combustion have observed upstream propagating pressure waves in the combustor during certain instances that resemble detonation waves or the onset of a deflagration to detonation event [44, 45, 46]. For the experiments in this study, similar behavior was observed in certain cases. Specifically, this was observed in a thermally-choked fueling condition. As shown in Figure 4.6, a total ϕ of 0.62 is injected through the first injector while the igniter remains on. Due to addition of fuel from injector 1, the flame blows out and unburnt fuel pools near the combustor exit. Efficient mixing of the unburnt fuel occurs due to the

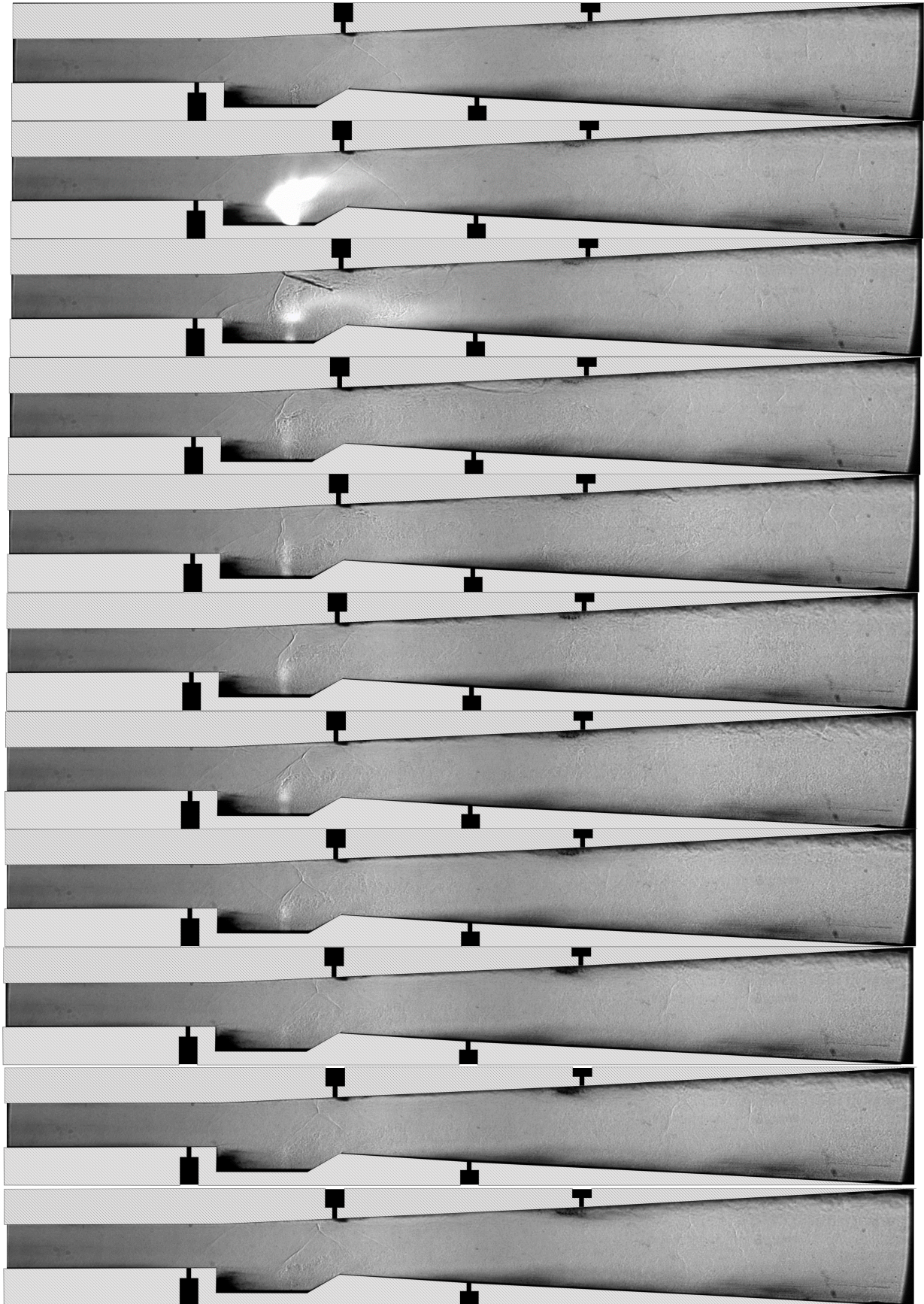


Figure 4.5: Schlieren sequence of a scramjet ignition event.

formation of turbulent structures in the flow. The fuel becomes entrained with the flowing air and becomes premixed. Therefore, the local equivalence ratio of the mixture increases at the combustor exit. When the mixture reaches the conditions necessary to spontaneously ignite, heat is released quickly which causes the formation of upstream propagating pressure waves to match the large temperature gradients present at the point of heat release. As the flow travels upstream, the heat release from the burning fuel and coalesced pressure waves start to become more coupled resembling more of a detonation-like structure. The wave seems to decouple at the cavity due to the rapid expansion, but completely dissipates past the first injector as there is no longer fuel to provide the heat release necessary to sustain the wave. Afterwards, the flow in combustor immediately transitions into a quasi-steady thermally choked mode operation with stable flame holding at the cavity.

Figure 4.7 shows the distance the wave travels in one frame and the corresponding velocity with respect to the combustor flow. The time between each frame captured is $31.25 \mu s$. Velocities of ~ 800 m/s are observed.

4.3 Single Injection

The next set of experiments characterized the single injection combustion events for various equivalence ratios. Figure 4.8 shows the normalized pressure trace for various equivalence ratios injected through injector 1. A strong pressure rise is observed in the cavity area in equivalence ratios higher than 0.31. This is indicative of a thermally choked mode operation whereas the equivalence ratios lower than 0.31 is expected to be in supersonic combustion mode as there is no strong pressure rise in the cavity area. Figure 4.8 also shows the pressure in the isolator rising to

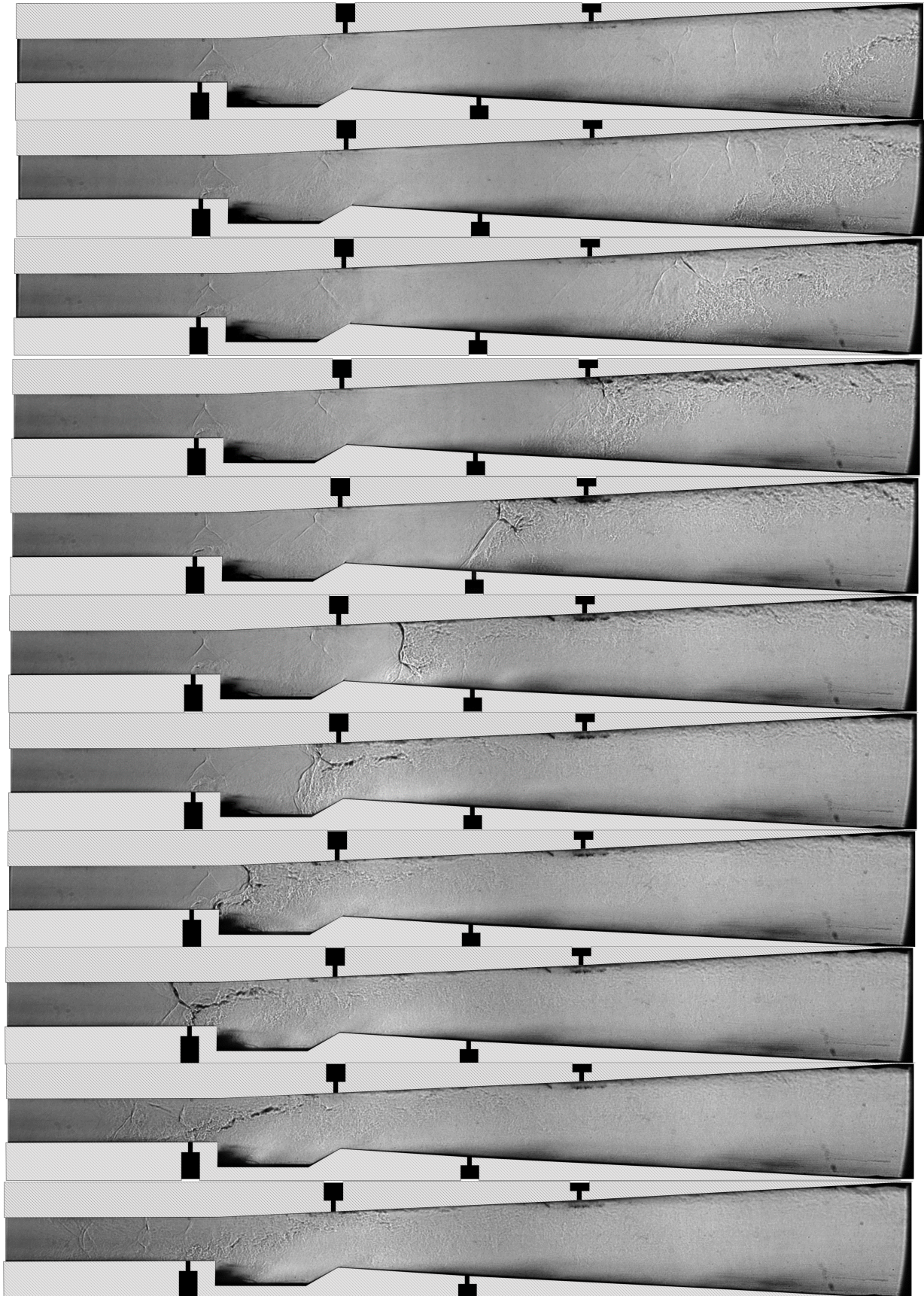


Figure 4.6: Schlieren sequence of a shock train formation after a flashback event during ignition.

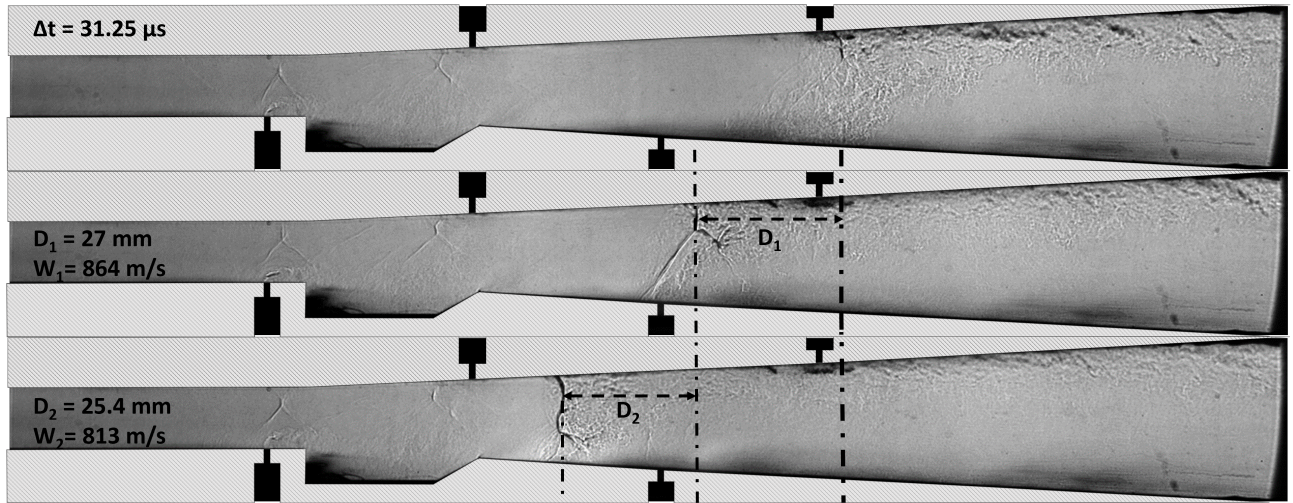


Figure 4.7: Schlieren frames of an upstream propagating shock wave during the ignition event.

contain the pressure rise in the combustor in all cases, but most notably in the thermally-choked cases. The ϕ of 0.20 case, or Case 1(a), establishes the pilot flame for the ensuing distributed injection cases. The ϕ of 0.52 case, or Case 1(b), was chosen as a reference for the distributed injection cases as it is a strong thermally choked case. The luminescence and schlieren images for a typical Case 1(b) run, shown in Figure 4.8 and 4.10 confirms a thermally choked mode operation as a normal shock train is observed in the isolator. Furthermore, the luminescence image depicts an oblique shock train downstream of the cavity, which means that the flow is expanding back to supersonic speeds after thermal choking due to area expansion. The luminescence image also shows the flame at the cavity ramp occupying the full cross-sectional area of the combustor at that point, which adds further evidence that the flow is choking in the cavity region. The image also shows evidence of a cavity-stabilized combustor operation and the flow through injector 1 does not ignite immediately upon exiting the injector, but instead ignites when it reaches the hot cavity wake flow. The injection jet through the first injector does not penetrate high enough into

the hot, core-flow to reach the auto-ignition temperature needed so a cavity is required for stable ignition.

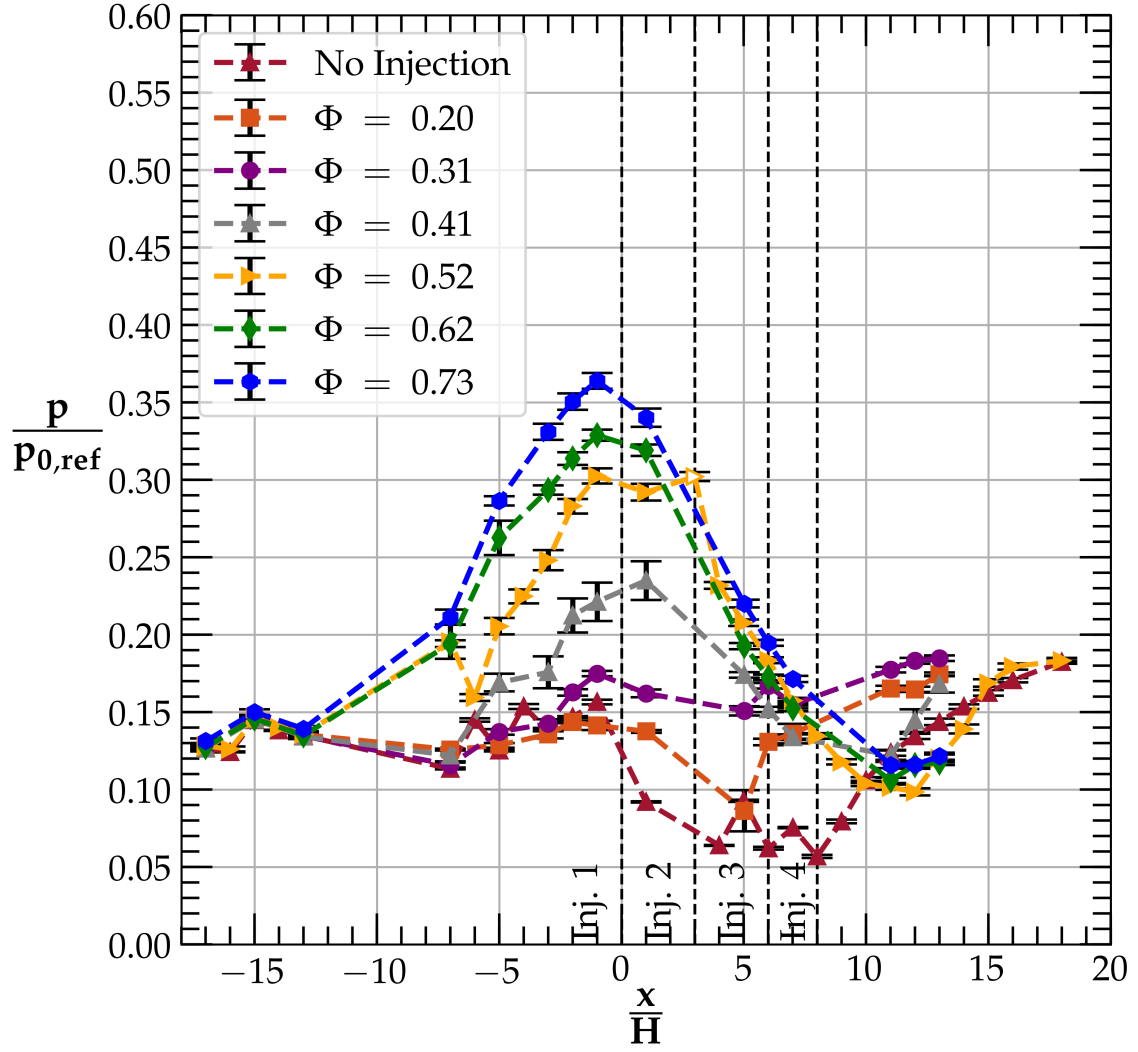


Figure 4.8: Combustor and isolator wall pressure distributions for single injection only and across various equivalence ratios.

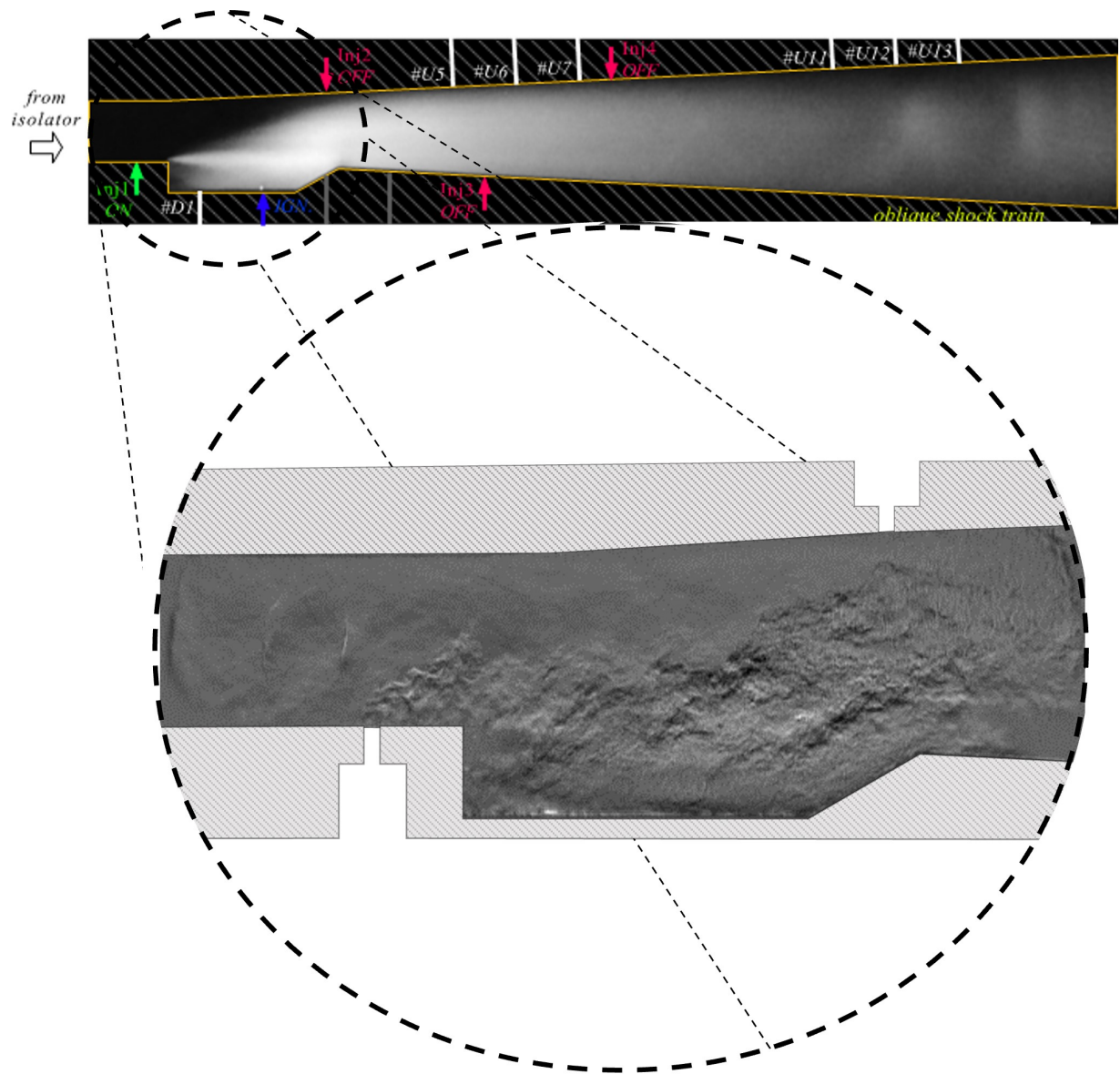


Figure 4.9: Broadband luminescence (top) and schlieren (bottom) of a typical thermal choking event and the case of single injection (Case1(b)).

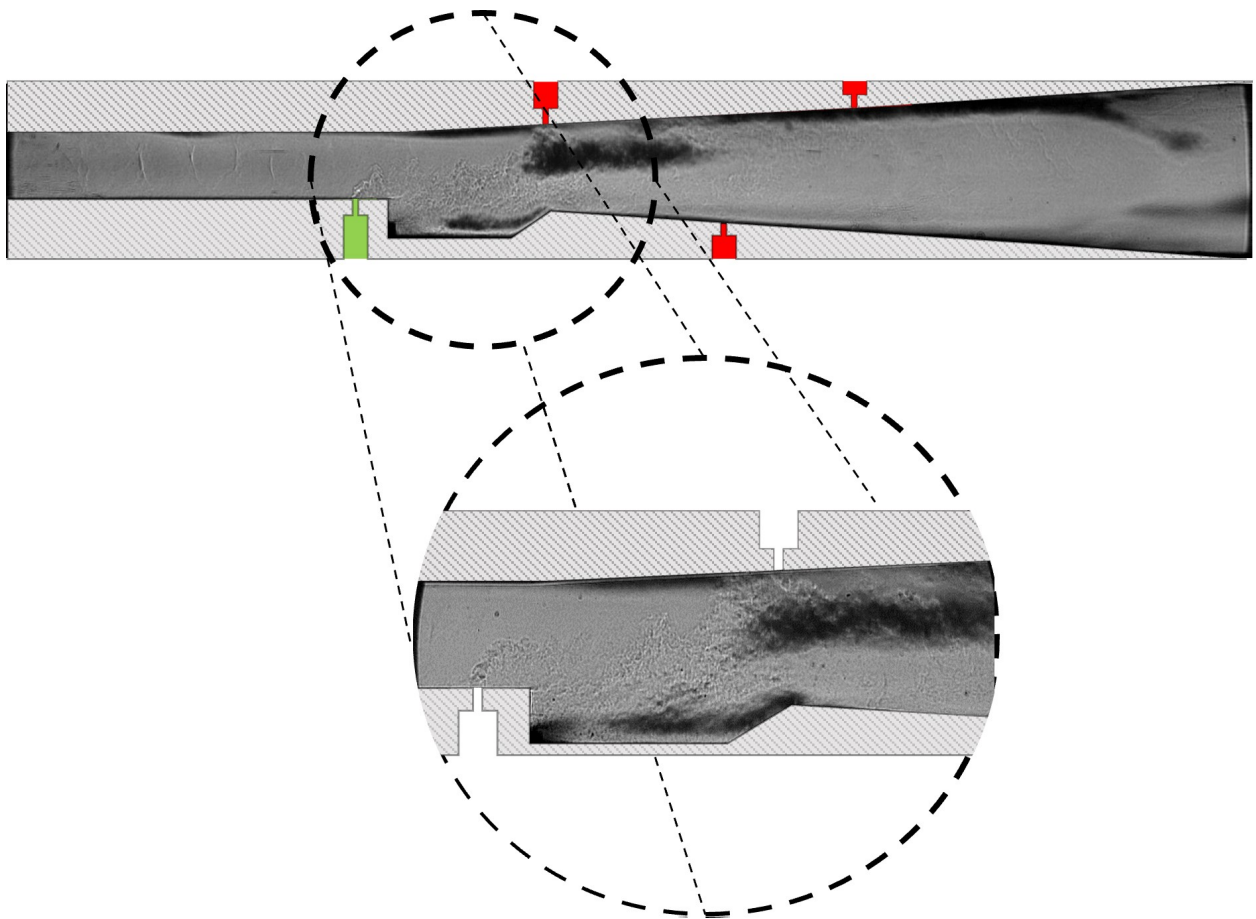


Figure 4.10: Wider view schlieren of a typical thermal choking event and the case of single injection (Case1(b)).

Chapter 5: Combustor Characterization

This chapter characterizes the dual-mode scramjet combustor operation across different distributed injection schemes while maintaining a constant equivalence ratio fueling condition. Furthermore, deduced heat release models are presented based on fundamental analysis as well as experimental data acquired.

5.1 Distributed Injection

As shown in Figures 4.8 and 4.9 and mentioned previously, single injection with a ϕ of 0.52, or Case 1(b), is shown to be a strong thermally choked case. As such, this equivalence ratio condition is chosen to compare the different injection schemes. In all the distributed injection cases, the first injector is ran at a ϕ of 0.20 and the remaining fuel is distributed across the other injectors for a total ϕ of 0.52. As shown in Figure 5.1, the distributed fuel injection schemes (Cases 2(a) and 2(b)) are characterized by a gradual pressure rise across the combustor as opposed to the abrupt, strong pressure peak observed in the cavity region of the thermally-choked single injection case of Case 1(b). This indicates that in the cases of distributed fuel injection despite injecting a similar amount of fuel as the thermally-choked Case 1(b), the combustor is operating in supersonic combustion mode. In Cases 2(a) and 2(b), the pressure trace in the isolator is also shown to not deviate too significantly from the baseline case as opposed to Case 1(b) where the

pressure in the isolator rises to match the strong pressure gradient in the combustor. Therefore, this suggests the presence of an oblique shock train in the distributed fuel injection cases. This is further confirmed by Figure 5.2 and 5.3 which show an oblique shock train formation in the combustor indicating supersonic flow. Similar to the single injection case shown in Figure 4.9, the flow through the first and top wall injectors do not immediately ignite and only achieve ignition after entering the cavity-wake flow as can be seen in the luminescence images. The darkened regions in the images captured in Figure 5.3 depict areas where the density gradient is particularly high, which may be due to intense burning or mixing occurring in those regions. Particularly, for the two injector case, there is a darkened region in the wake of the second injector as it mixes with the hot, cavity wake flow. Furthermore, the second injector is seen to have higher penetration into the cross-flow than the same injector in the four injector case. This is due to a larger ϕ being injected which translates to a higher jet momentum/velocity.

5.2 Heat Release

Rahimi and Chelliah [47] looked at using a quasi-one dimensional analysis to identify the thermal choking limits in a variable-area scramjet combustor duct and showed reasonable agreement with experimental results. For this study, through a combination of experimentally acquired thermodynamic properties at select locations, observations from flow visualization information, and one-dimensional diabatic flow analysis, an inverse problem of local heat release and local flow Mach number was formulated. Specifically, by using an assumption of steady one-dimensional flow with reversible heat transfer along with experimental data and Mach numbers known at certain points along the combustor, a heat release profile can be deduced as shown by Figure

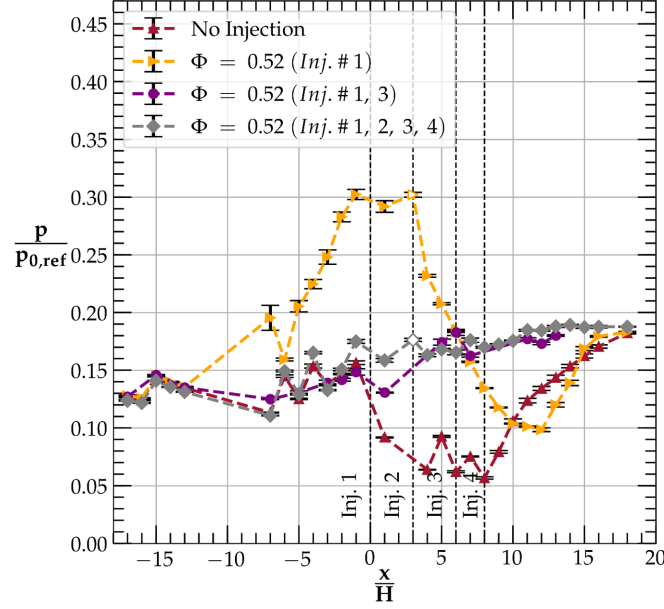


Figure 5.1: Combustor and isolator wall pressure distributions comparing Cases 1 and 2 or single injection to distributed injection.

5.4. In the case of single injection, the location of thermally choking was assumed based on past results as well the imaging diagnostics obtained. Knowing the total amount of heat required to choke the flow based on the geometry and flow conditions measured, the heat release profile for single injection was calibrated up until the point of thermal choking using an intensity profile obtained from the broadband luminescence images. By applying one-dimensional Rayleigh flow with expansion, the remaining portion of the heat release profile is deduced until the point of boundary layer separation at which point the assumption of one-dimensional flow fails. The calculations for the analysis is presented in more detail in the appendix. The total heat release in the combustor is used to normalize the heat release data and is determined from the total amount of fuel added to the flow. The integral area of the heat release distribution shown in Figure 5.4 for both single injection and distributed injection should be and are similar as an equivalent amount

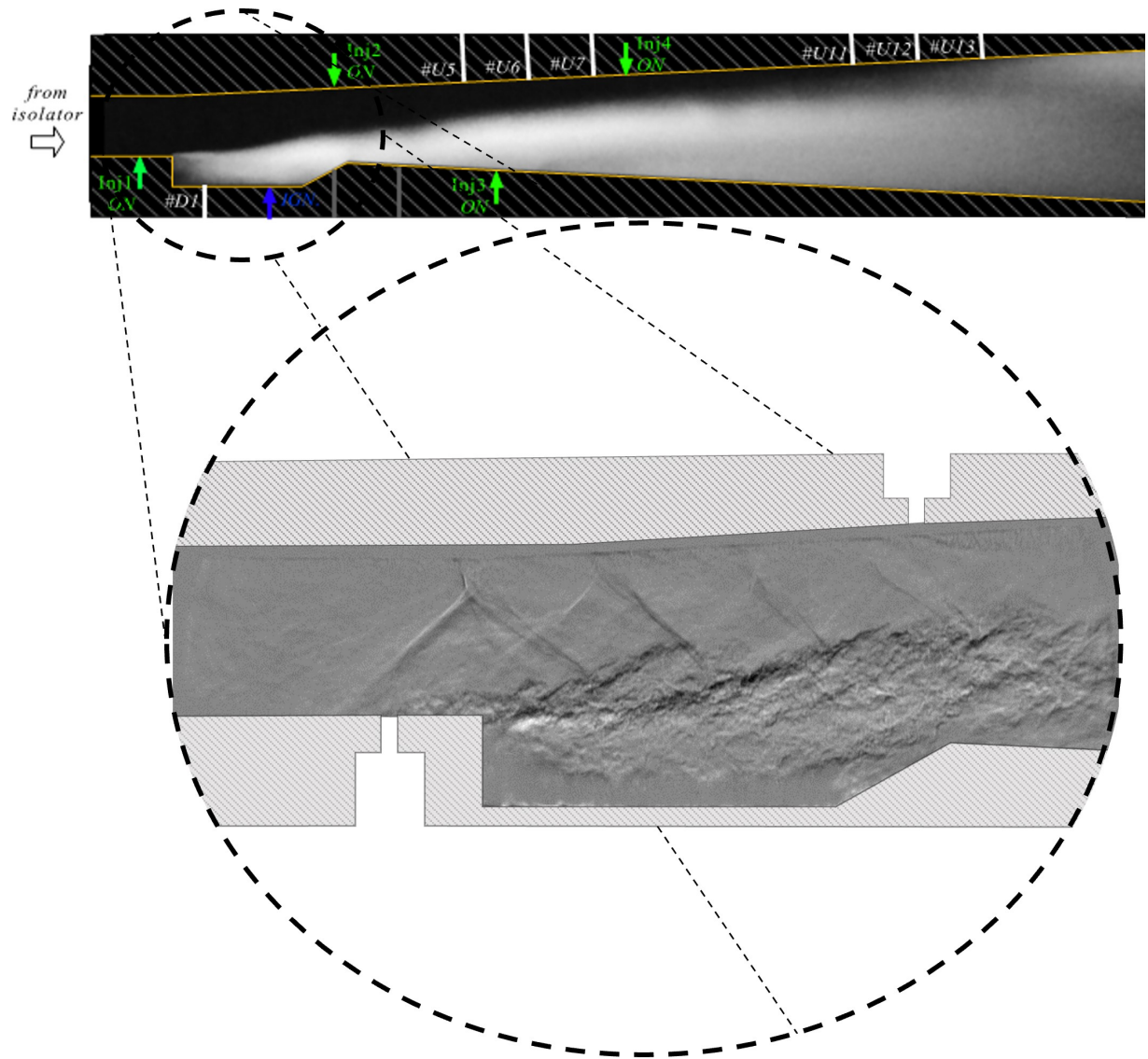


Figure 5.2: Broadband luminescence (top) and schlieren (bottom) of a typical supersonic combustion event.

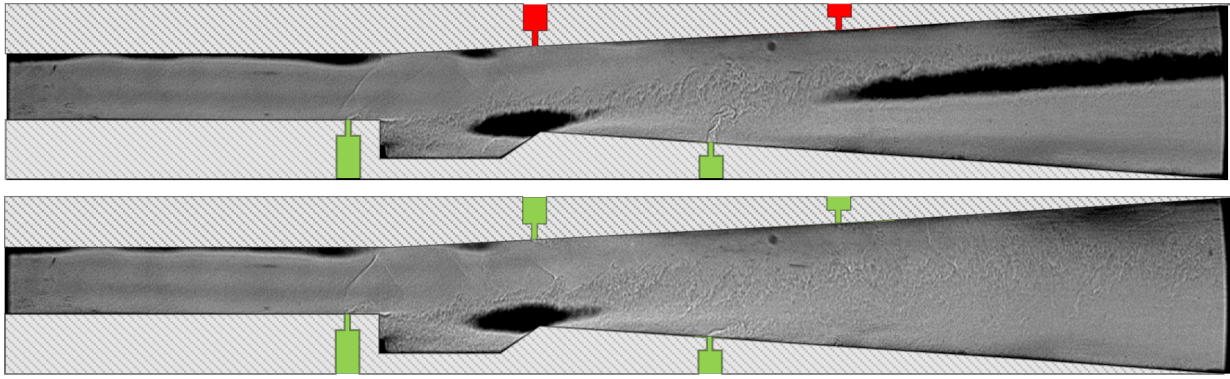


Figure 5.3: 10 in. (254 mm) schlieren of typical supersonic combustion events with two-injector configuration (Case1(a) on top and four-injector configuration (Case1(b)) on bottom.

of fuel is injected in both cases.

Altering the fuel distribution schemes demonstrated significant effects on the heat release distribution along the combustor. In the case of single injection, as can be seen in Figure 5.4, more of the heat release is shown to be concentrated in the cavity region where the area is more confined. This is conducive of a thermally choked mode event as larger amounts of heat are added to a smaller area. In the case of distributed injection, heat release is added more evenly to larger and larger cross-sectional areas, and therefore, more heat can be added before the flow becomes thermally-choked.

5.3 Velocity and Mach Number

Using the heat release profile, Mach number can be deduced using a Rayleigh flow analysis as shown by Figure 5.5. At the point $x/H = 2$, the flow is seen to be thermally choked in the visualizations obtained and as such reaches a Mach number of 1. Following this point, as shown in Figure 5.5 and, in the case of single injection, the flow proceeds to accelerate back to

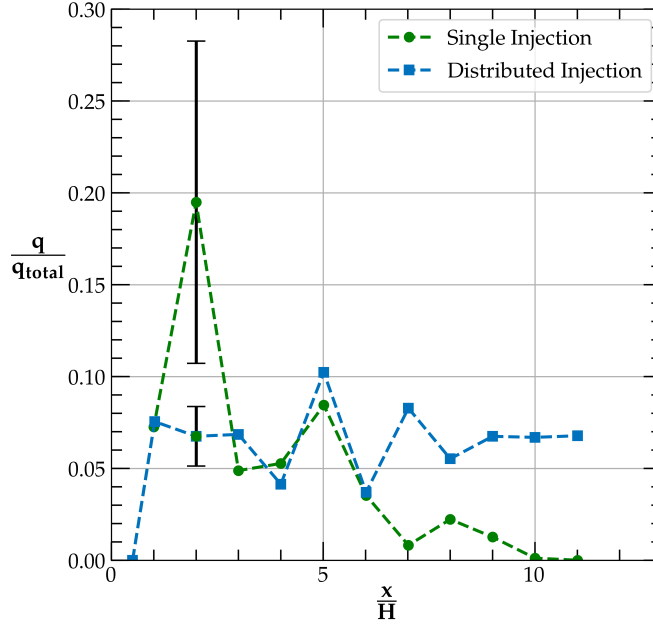


Figure 5.4: Normalized heat release profile attained from experimental data and quasi-one dimensional analysis.

supersonic speeds as it enters areas of expanding cross-sectional area and decreasing heat release. In distributed injection, however, the isolator exit/combustor inlet Mach number is much higher despite the formation of oblique shock trains in the isolator, and the local Mach number also gradually decreases as more heat is added along the combustor. Correspondingly, local velocity information can be deduced using Rayleigh analysis. This is compared to the direct velocity measurements from the 2pFLDI velocimetry technique.

Overall, the 2pFLDI velocimetry obtained data agrees well with what is physically understood is happening in the combustor. Figures 5.6 and 5.7 compare velocities obtained from both a 2pFLDI technique and velocities deduced using Rayleigh Flow analysis. Figure 5.7 shows that in the case of distributed injection the velocity stays relatively steady as the rate of combustor area increase seems to balance out the rate of density decrease as a result of heat addition. On the other

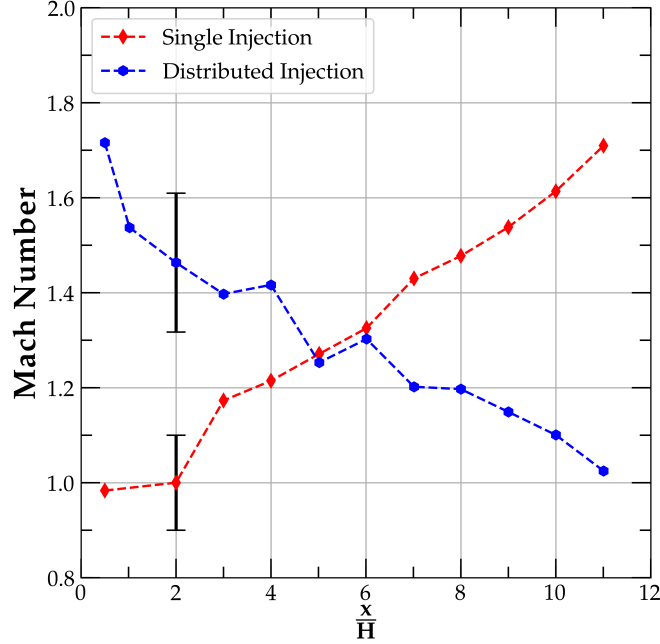


Figure 5.5: Local Mach number profile attained from experimental measurements and quasi-one dimensional analysis.

hand, in Figure 5.6, in the single injection case, the velocity increases as the flow approaches the combustor exit as the combustor area increases with negligible heat release occurring towards combustor exit. In Figure 5.6, the 2pFLDI velocity reaches its lowest point at $x/H = 2$, which is consistent with the fact that flow is observed to be choked at some point in the cavity area. Subsequently, the flow expands back to supersonic speeds which is also consistent with the deduced heat release analysis and the luminescence data of the single injection case as shown in Figure 4.9. In the single injection case, from both the pressure data and from observation, boundary layer separation is shown to occur at around $x/H=11-12$. Both the 2pFLDI-obtained and deduced velocities show a sharp decrease after this point as the flow shocks up to match the pressure of the combustor exit. In the distributed injection case of both the deduced velocity and the measured velocity, the flow remains supersonic throughout.

In the case of the deduced velocity points, the flow is assumed to be one-dimensional, while in reality scramjet combustor flow is highly three dimensional so in order to definitively say if either the deduced velocity or the 2pFLDI velocimetry (a relatively new application of 2pFLDI) accurately predict velocity in this situation, a comparison to velocities obtained with other known, proven velocimetry techniques is needed, but some confidence can be attained in that the deduced velocity are of a similar order of magnitude to the FLDI data and with some overlap while also being consistent with what is physically expected.

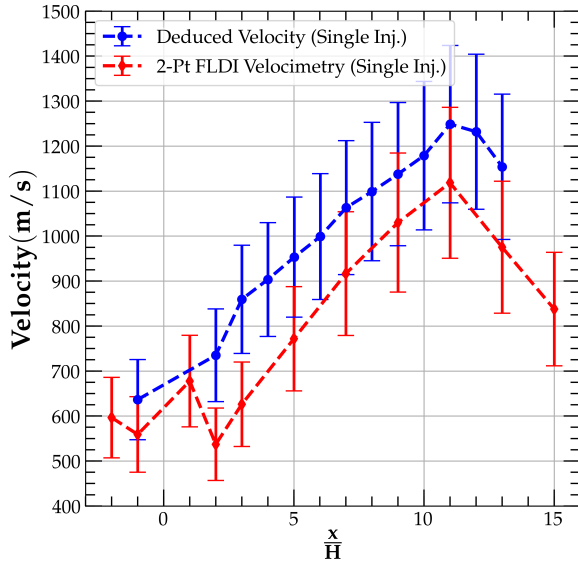


Figure 5.6: Deduced local velocity profile attained from experimental measurements and quasi-one dimensional analysis as well as measured velocity attained from 2pFLDI for Case 1(b).

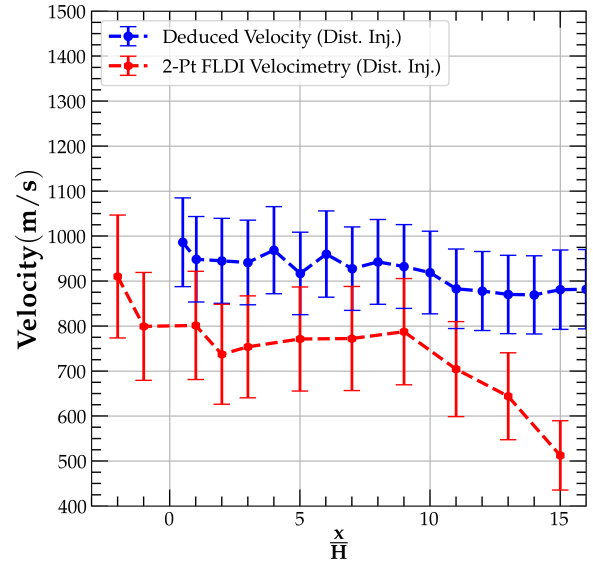


Figure 5.7: Deduced local velocity profile attained from experimental measurements and quasi-one dimensional analysis as well as measured velocity attained from 2pFLDI for Case 2(b).

Figure 5.8 shows a vertical velocity profile obtained from the using 2pFLDI technique. Again, the profile is consistent with what is observed to be physically occurring within the combustor. The velocity profile is asymmetric consistent with the asymmetric combustor geometry which has a cavity. The technique may also be showing certain flow features which would need to be further

verified. For instance, the flow in the combustor is highly heterogeneous. The flowfield may be showing cold, slow-moving reactants, hot, fast-moving products, or mixing shear layers between the two. The velocity field obtained using the technique may be highlighting these different flow features.

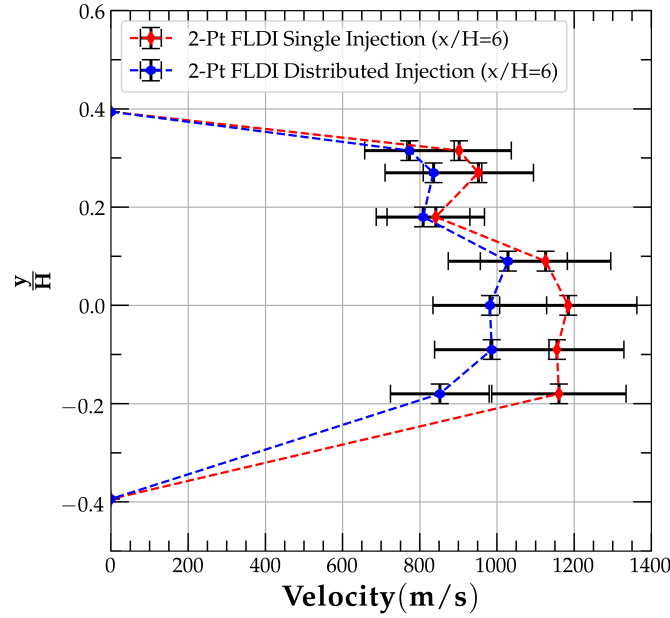


Figure 5.8: Vertical velocity profile measurements obtained from applying a 2pFLDI velocimetry technique.

The signals obtained from the 2pFLDI technique are used to obtain velocity by cross-correlating the signals. A characteristic time lag of the flow structure passing through the foci of the beam is determined. In the post-processing of these signals, a $500 \mu\text{s}$ window and a conditional filter is applied to ensure data integrity and quality for the vertical and axial velocity data shown in Figures 5.6, 5.7, and 5.8. The condition chosen for the filter is that the normalized cross-correlation must be greater than 30 %. Figures 5.9 and 5.10 show that the velocity data converges using a $1000 \mu\text{s}$ window. However, at smaller timescale windows, the measurements

start to deviate and the uncertainty becomes significantly larger. This may be due to larger-scale structures present in the flow that may bias the measurement, as a large structure passing through the foci may be regarded as a fast-moving, small structure. Furthermore, different levels of conditional filtering are applied on the data to filter based on how well the signals are cross-correlated to each other. Figures 5.11 and 5.12 show unfiltered, centerline velocity measurements at $x/H = 3$ within the combustor for the single and distributed injection cases, respectively. Correspondingly, Figures 5.13 and 5.14 show the probability density functions of the unfiltered velocity measurements for both cases. As seen in the figures, a range of velocity is reported as well as negative velocities. In past studies on the applications of the 2pFLDI velocimetry technique, the velocities obtained were known to under-predict in some cases due to contamination from the slower moving boundary layer flow [41]. Furthermore, the depth of focus of the 2pFLDI technique is on a similar order of magnitude as the channel width where the measurement is taken and so there is a possibility that the slower-moving boundary layer flow is influencing the measurements in the form of the slower velocity outliers. Moreover, the reacting flow field may have local regions of re-circulation, such as in the cavity region, where negative velocities are possible. Negative velocities, however, would not be expected in the centerline of the combustor. Therefore, the negative velocity measurements, in this case, were seen as non-physical and add evidence to why a conditional filter is necessary. When looking at the probability density functions of the data, Figures 5.13 and 5.14 indicate a somewhat Gaussian distribution with a defined mean in the data. Correspondingly, the mean and median velocities obtained from these measurements, as can be seen in Table 5.1, are more consistent with velocities expected of the core flow in the combustor.

Figures 5.15 and 5.16, show application of conditional filtering to ensure higher data

integrity by only accepting well-correlated velocity measurements. As can be observed in Figures 5.15 and 5.16, when the data is filtered for only velocities with normalized cross-correlation greater than 30 %, much of the slower velocity outliers (which may be due to the slower-moving boundary layer flow) and all the negative velocity points are filtered out. Furthermore, a stronger normal distribution also appears with average speeds that are expected in the combustor for the corresponding injection scheme. In fact, in the case of distributed injection, where the flow is expected to be highly supersonic in the combustor and much faster than the thermally choked single injection case, the mean velocity increased from 740 m/s to 919 m/s as shown in Table 5.1. Filtering at higher cross-correlations still in Figures 5.19 and 5.20, however, indicated a greater a loss of resolution near the mean data points with comparatively little change in the mean and median velocities from the 30 % cross-correlation condition. Therefore, a conditional filter of 30 % was chosen to analyze the velocity data. Moreover, the probability density plots shown in Figures 5.17, 5.18, 5.21, and 5.22 did not seem to change significantly as higher cross-correlation filters are applied. Figures 5.23, 5.24, 5.28, 5.27, 5.31, and 5.32 depict centerline velocities obtained in the isolator at $x/H = -2$. The distributions of the velocity shown in Figures 5.25, 5.29, 5.33, 5.26, 5.30, and 5.34, indicate a more bimodal distribution compared to measurements attained within the combustor. Increasing the minimum cross-correlation level when filtering the measurements did not attenuate the slower velocities. In Figures 4.10 and 5.2, normal and oblique shock trains are observed in the single and distributed cases respectively. Depending on which side of the shock the measurements are taken, the flow could be supersonic or subsonic in the single injection case. In the distributed injection case, depending on which side of the oblique shock the measurement are taken, the flow speed will still be supersonic, but significantly slower or faster. Furthermore, Table 5.1 indicates larger difference between the

mean and median velocities in the isolator when compared to the combustor measurements. This coupled with the more bimodal distribution shown for the measurements taken in the isolator highlight the difference in characteristics of flow structures in the isolator versus the combustor.

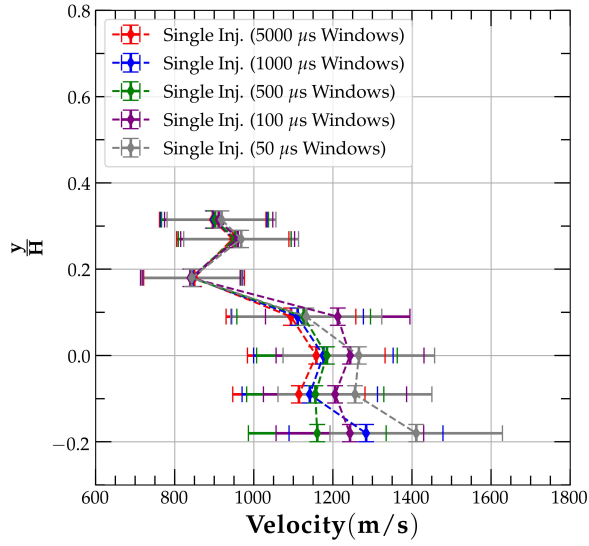


Figure 5.9: 2pFLDI vertical velocity profile for the single injection case across different windowing schemes.

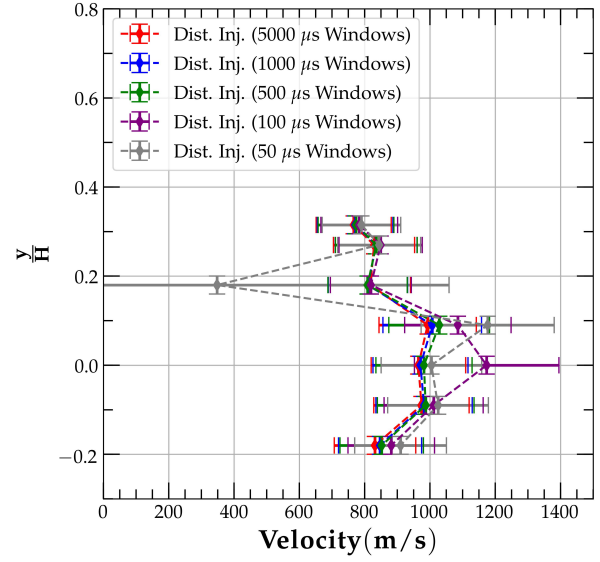


Figure 5.10: 2pFLDI vertical velocity profile for the dist. injection case across different windowing schemes.

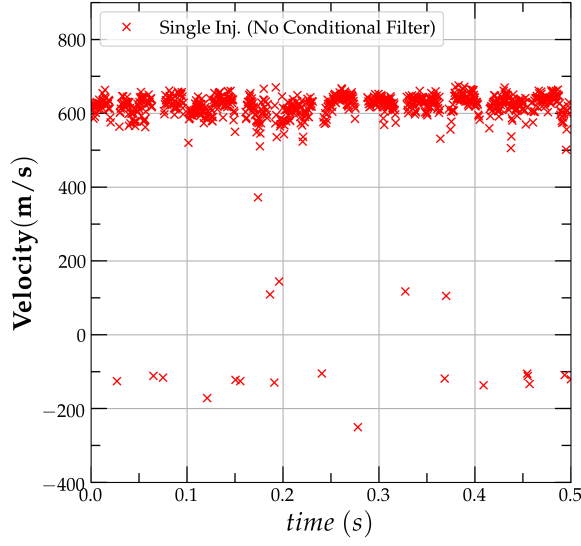


Figure 5.11: 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = 3$ with no filtering.

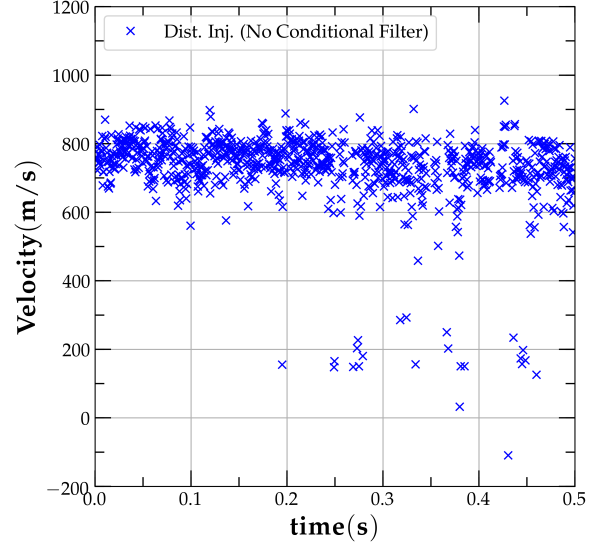


Figure 5.12: 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = 3$ with no filtering.

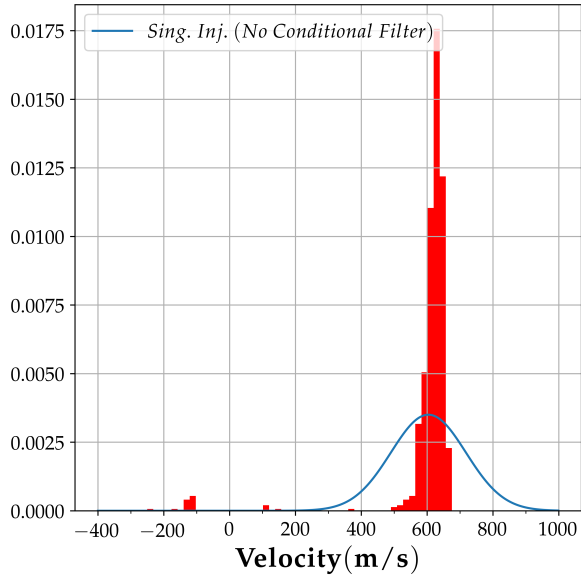


Figure 5.13: Probability density function of 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = 3$ with no filtering.

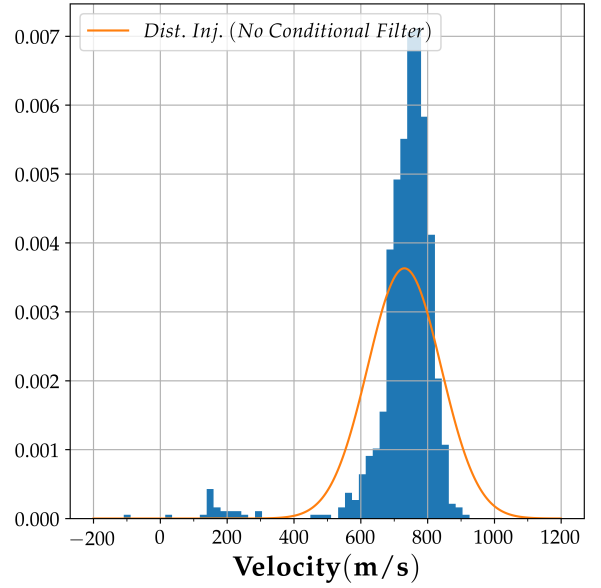


Figure 5.14: Probability density function of 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = 3$ with no filtering.

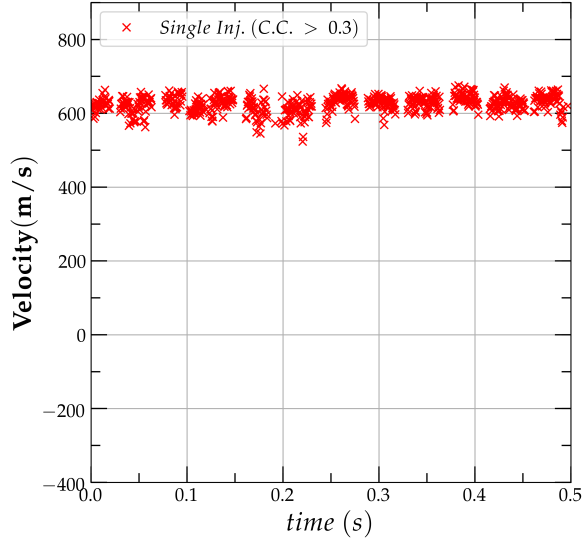


Figure 5.15: 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.3 only).

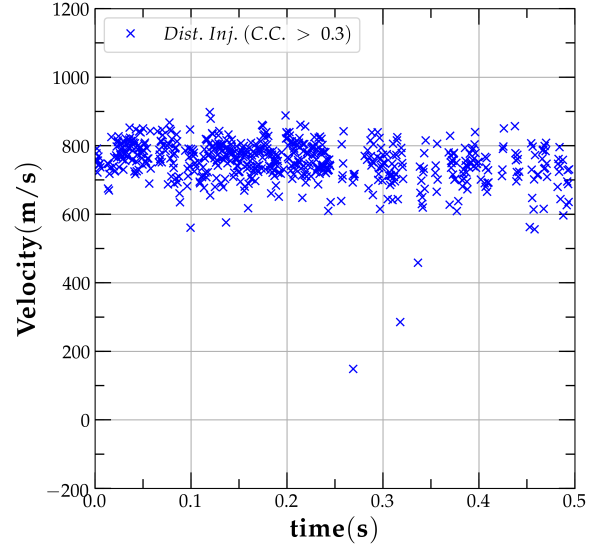


Figure 5.16: 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.3 only).

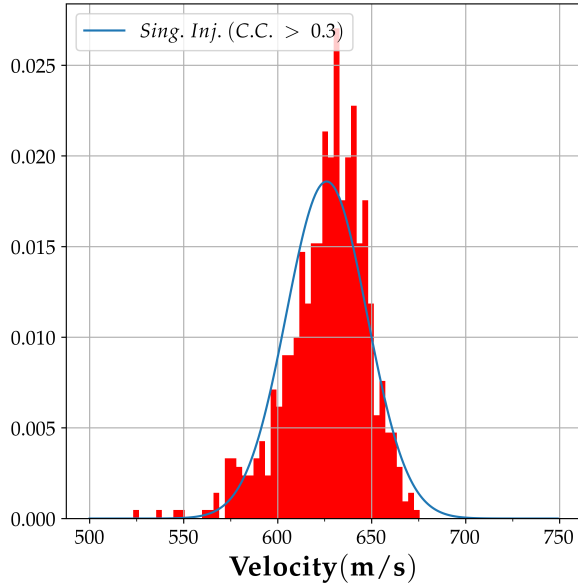


Figure 5.17: Probability density function of 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.3 only).

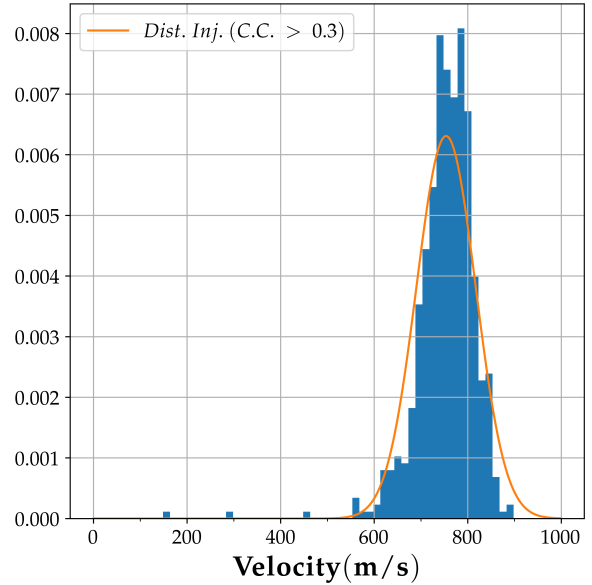


Figure 5.18: Probability density function of 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.3 only).

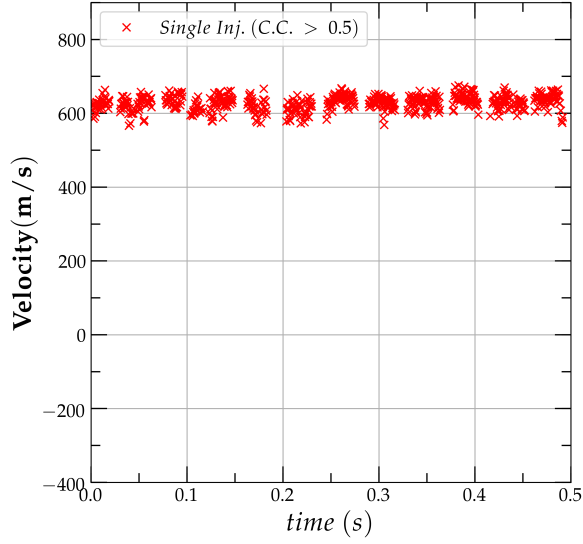


Figure 5.19: 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.5 only).

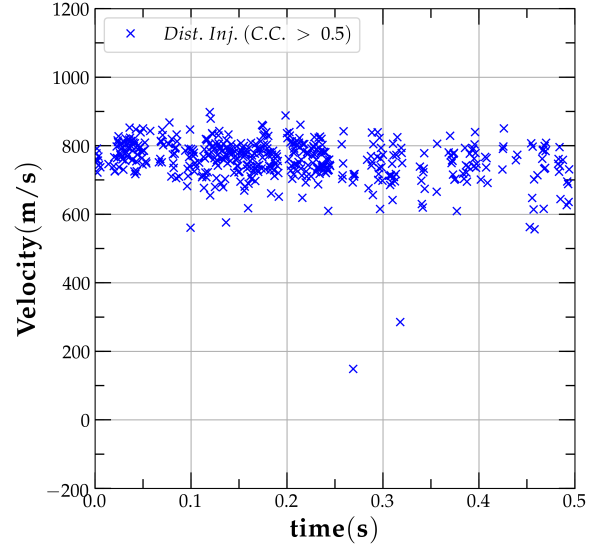


Figure 5.20: 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.5 only).

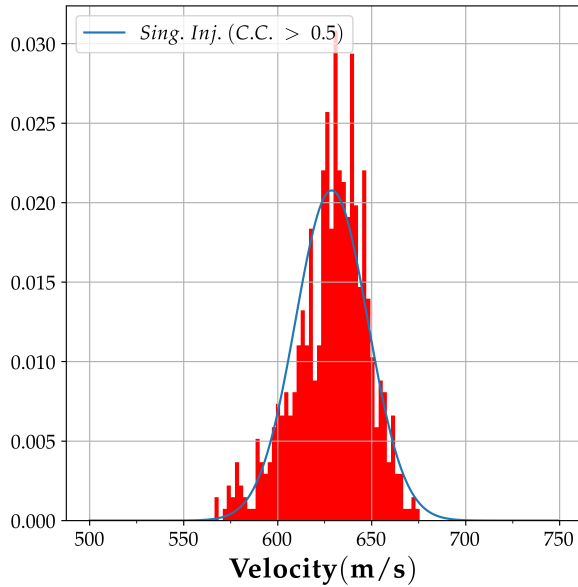


Figure 5.21: Probability density function of 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.5 only).

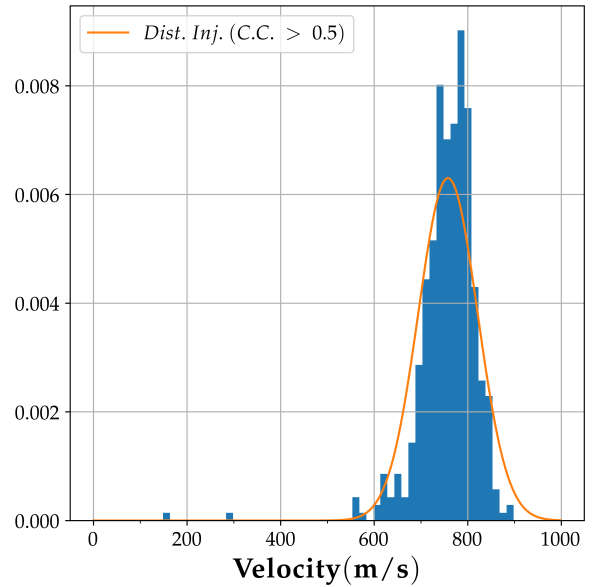


Figure 5.22: Probability density function of 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = 3$ with filtering (normalized cross-correlation > 0.5 only).

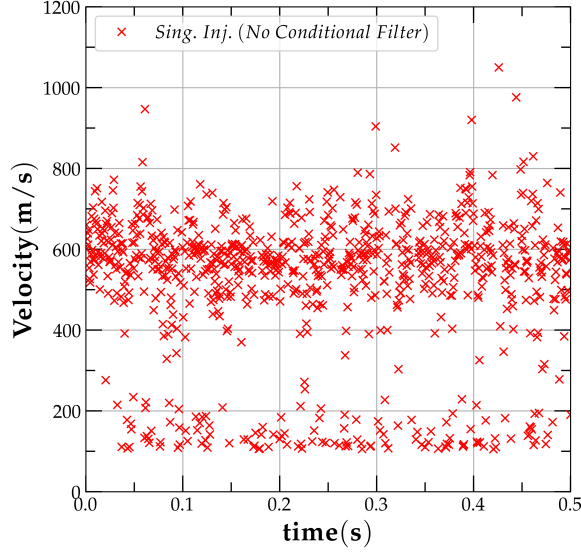


Figure 5.23: 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = -2$ with no filtering).

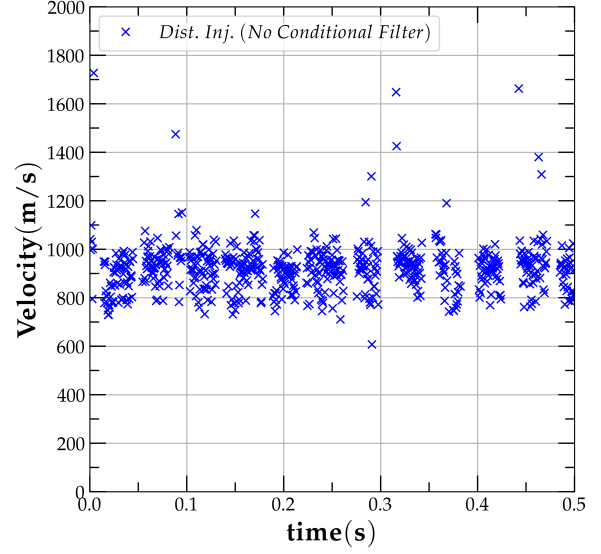


Figure 5.24: 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = -2$ with no filtering.

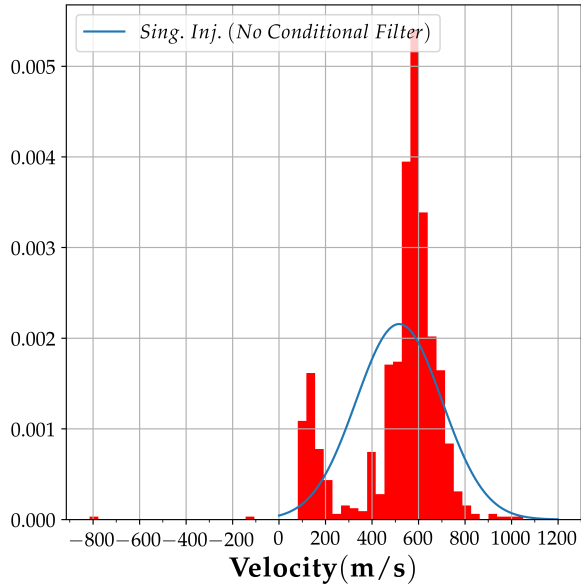


Figure 5.25: Probability density function 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = -2$ with no filtering).

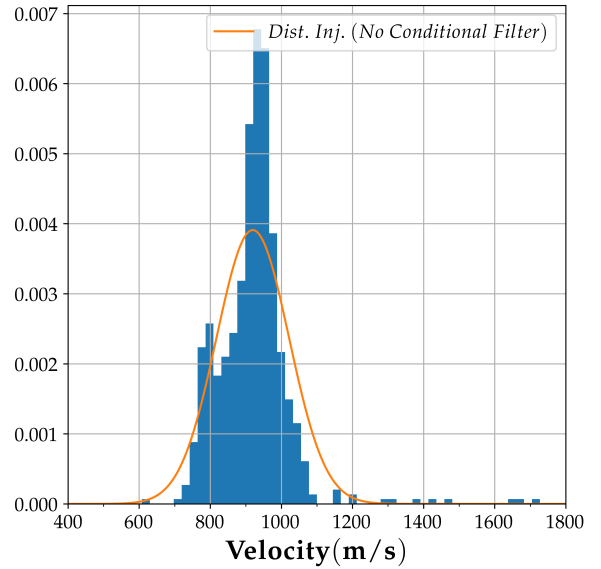


Figure 5.26: Probability density function of 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = -2$ with no filtering.

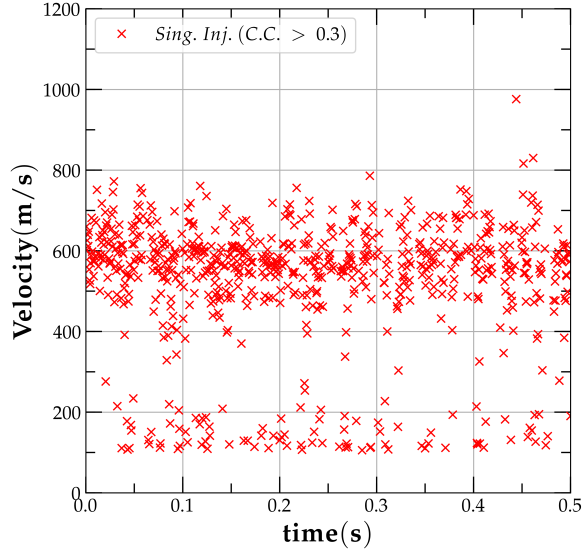


Figure 5.27: 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.3 only).

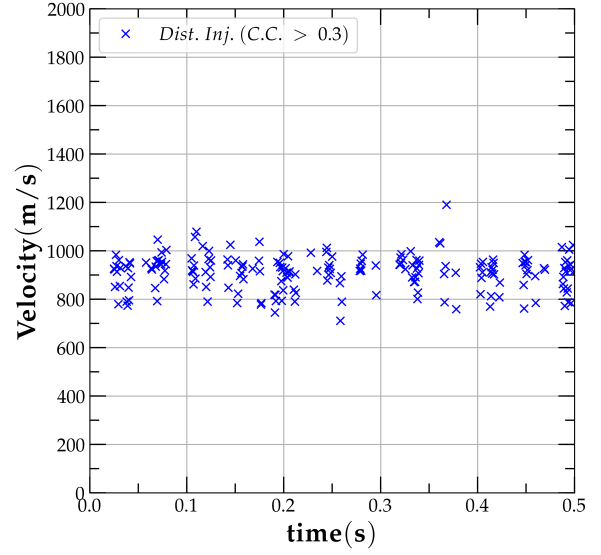


Figure 5.28: 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.3 only).

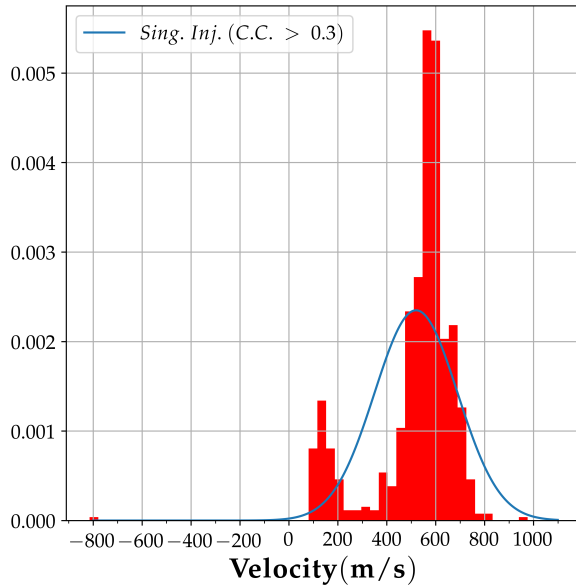


Figure 5.29: Probability density function of 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.3 only).

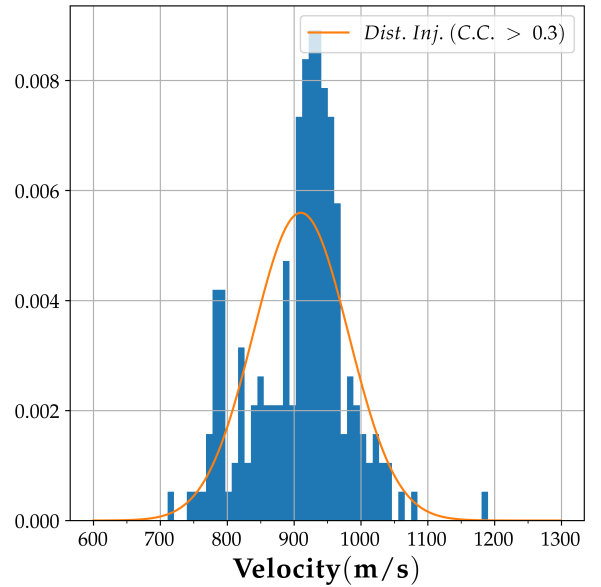


Figure 5.30: Probability density function of 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.3 only).

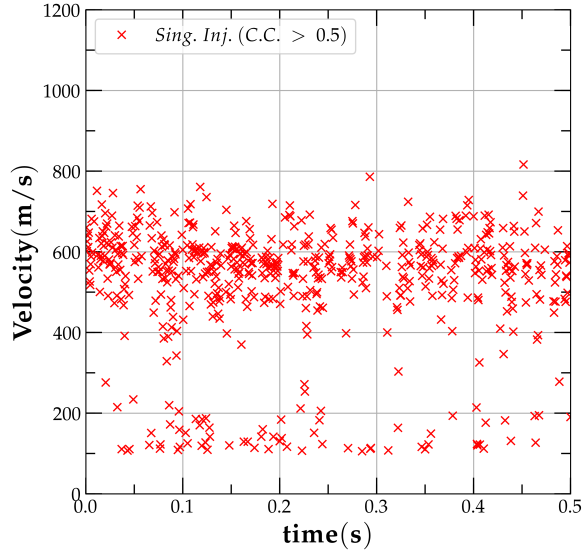


Figure 5.31: 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.5 only).

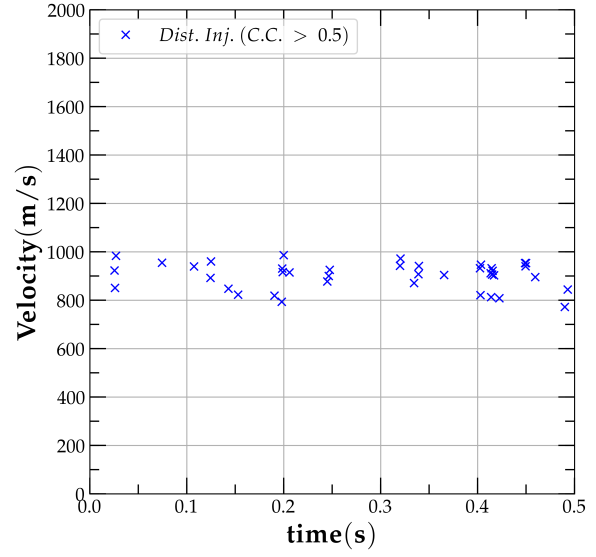


Figure 5.32: 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.5 only).

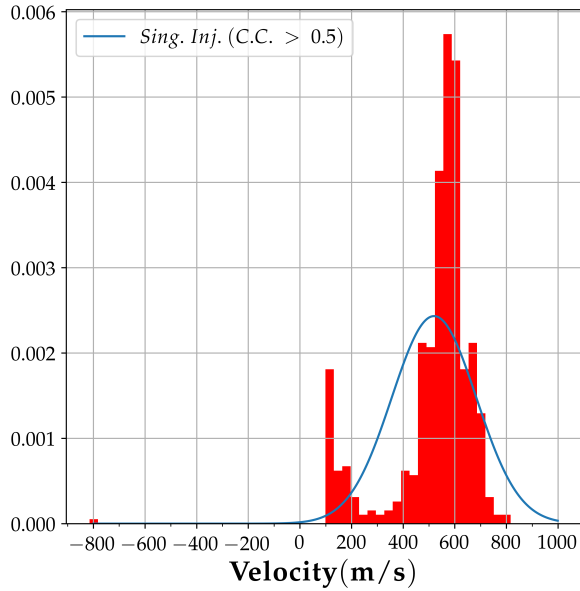


Figure 5.33: Probability density function of 2pFLDI time-dependent velocity measurements for the single injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.5 only).

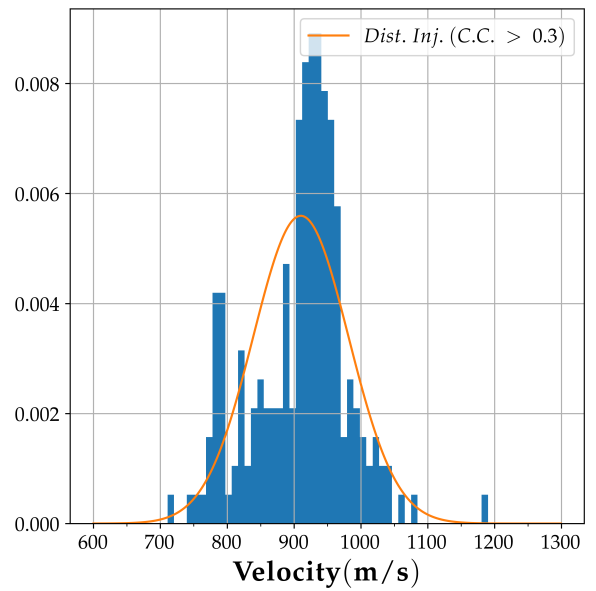


Figure 5.34: Probability density function of 2pFLDI time-dependent velocity measurements for the distributed injection case at $x/H = -2$ with filtering (normalized cross-correlation > 0.5 only).

Table 5.1: Average and median velocities for each case.

Injection Scheme	Location	Filtering	Mean (m/s)	Median (m/s)
<i>Single Injection</i>	$x/H = 3$	No Filter	604	626
<i>Distributed Injection</i>	$x/H = 3$	No Filter	740	750
<i>Single Injection</i>	$x/H = 3$	$CC > 0.3$	626	626
<i>Distributed Injection</i>	$x/H = 3$	$CC > 0.3$	919	922
<i>Single Injection</i>	$x/H = 3$	$CC > 0.5$	629	631
<i>Distributed Injection</i>	$x/H = 3$	$CC > 0.5$	901	913
<i>Single Injection</i>	$x/H = -2$	No Filter	517	569
<i>Distributed Injection</i>	$x/H = -2$	No Filter	920	926
<i>Single Injection</i>	$x/H = -2$	$CC > 0.3$	520	567
<i>Distributed Injection</i>	$x/H = -2$	$CC > 0.3$	919	922
<i>Single Injection</i>	$x/H = -2$	$CC > 0.5$	520	566
<i>Distributed Injection</i>	$x/H = -2$	$CC > 0.5$	901	913

Chapter 6: Combustor Mode Transition Study

This chapter demonstrates active control of the dual-mode scramjet combustor and control over the combustor mode transition using a system of fuel scheduling and a distributed fuel injection scheme.

6.1 Active Control

In real world scenarios, various, impromptu flight scenarios would require different modes of combustion operation, therefore, ideally, a method of switching between different modes of operation is needed. In the previous sections, stable modes of operation are established by altering the fuel injection distribution. Case 1(b) established a stable thermally-choked mode operation, while Cases 2(a) and 2(b) established a stable, supersonic combustion event, while all cases maintained a total ϕ of 0.52. Cases 3(a) and 3(b) characterizes the switch between different fuel injection schemes while maintaining the equivalence ratio as constant. The sequencing is designed to have a conservative 0.1s overlap so for Case 3(a) this overlap occurs as the flow transitions from single injection to distributed injection, and, for Case 3(b), it occurs during the transition between distributed injection and single injection. This is shown in Figure 6.1 where there is a pressure rise at $x/H = 1$ as the valve sequencing occurs and the fuel distribution scheme transitions from one to the other.

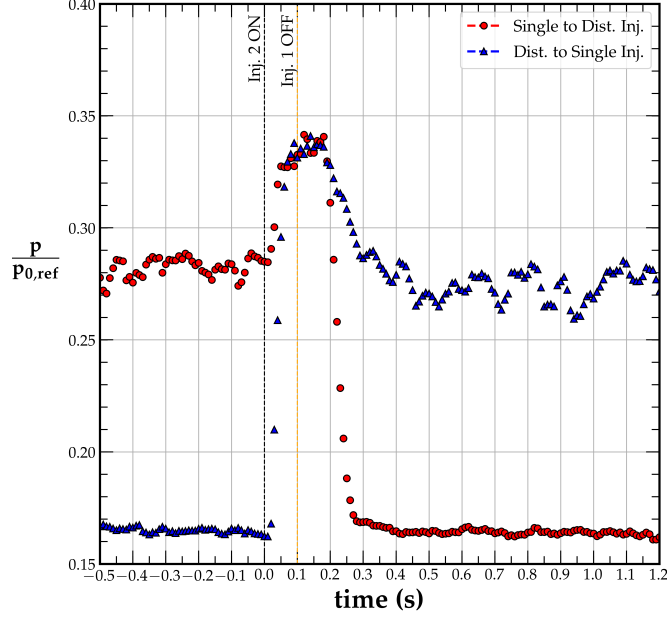


Figure 6.1: Wall pressure vs. time during active control sequencing at $x/H = 1$ in the combustor.

In both Case 3(a) and 3(b), the fueling condition is maintained at a ϕ of 0.52. Figure 6.2 show the pressure time trace for Case 3(a) and the transition between stable, thermally-choked mode operation to stable, supersonic combustion operation. Figure 6.3 depicts Case 3(b) and the transition from stable supersonic combustion mode to stable thermally choked mode operation. The static wall pressure data shows this transition to occur on the order of 0.3 s for both cases, but luminescence data captured at 10,000 Hz for Case 3(b), as seen in Figure 6.4, shows this transition to be much shorter on the order of 1 msec. Figure 6.4 also shows during the transition the flame rapidly blows off before re-establishing itself in its new mode. As the active control mechanism switches between one injection scheme to the other, any residual air in the fuel line will cause the flame to blow off and cause the local equivalence ratio to rise downstream. In Figure 6.4 a flashback event is seen as the flow reestablishes itself in a supersonic combustion mode and

returns to being a stable cavity-stabilized flame. Figure 6.4 also shows the flame being jet-stabilized briefly during the transition before becoming and remaining a cavity-stabilized flame again.

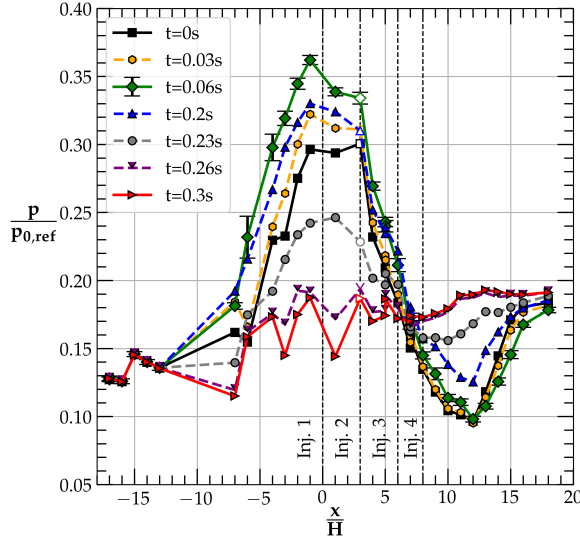


Figure 6.2: Temporal progression of wall pressure trace during actively controlled mode transition of Case 3(a) (single to distributed).

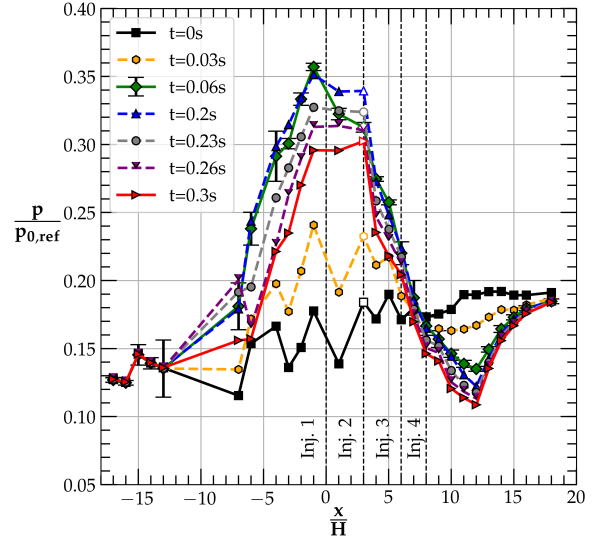


Figure 6.3: Temporal progression of wall pressure trace during actively controlled mode transition of Case 3(b) (distributed to single).

The longer response seen with the static wall pressure data is just an indication of the slow response time characteristic of the capillary tubing instrumentation system used to capture data and is not a reflection of the actual transition time. The actual transition time presented by the luminescence images is significantly different from natural combustor mode transition which occurs on a much longer time scale. Past studies have shown natural mode transition to occur on timescales of approximately 500 msec with frequent mode hopping events as well as large-scale sporadic flame movements that affect stable operation of the combustor [12]. Smaller time scales to mode transition are ideal because the longer time scales of natural mode transition are conducive to combustion instabilities occurring. Furthermore, the active control tests have

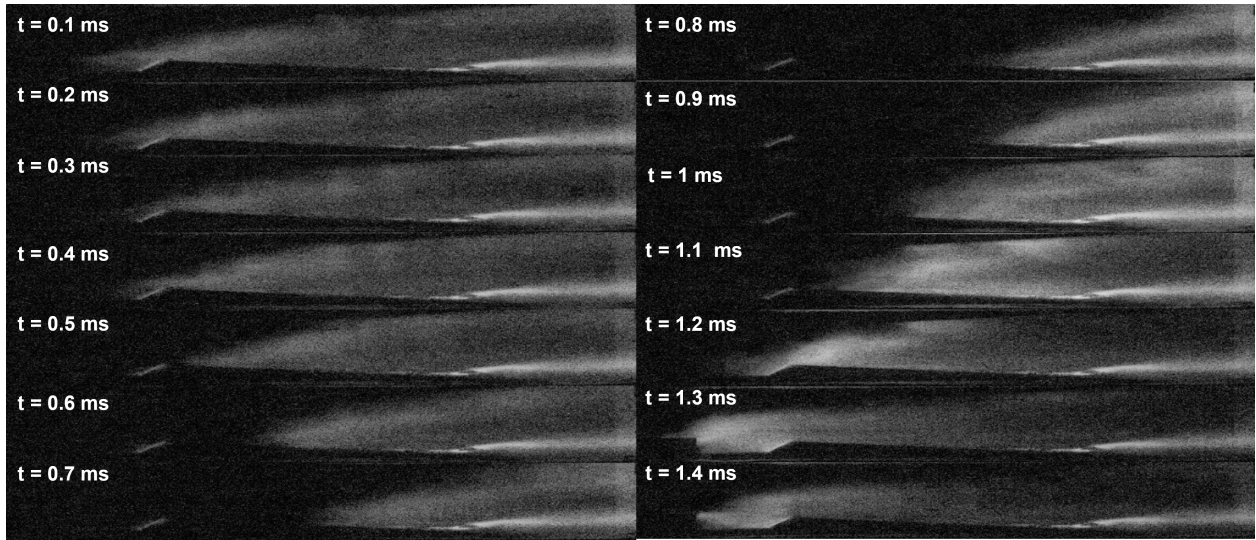


Figure 6.4: Series of high-speed luminescence images at different time intervals depicting the rapid mode transition event from supersonic combustion mode to thermally-choked mode.

demonstrated the possibility of switching between different modes of combustion systematically by changing the fuel injection scheme. This allows for more stability and, ultimately, greater flexibility in engine operation.

Chapter 7: Summary and Conclusions

The effects of axially distributed fuel injection on combustor performance were investigated experimentally using a dual-mode ramjet-scamjet model combustor. To achieve this, the UMD vitiated airflow facility was used to simulate the high enthalpy conditions of Mach 5 flight by mixing combustion products with make-up oxygen to match the oxygen concentration of air. A fuel injection system was developed consisting of a series of fast-response solenoid valves, manifolds, and transverse injectors to control the fuel distribution within the combustor. Three different distributed fuel injection schemes were ran: injection through the first injector only, injection through two injectors, and injection through all four injectors. The scamjet combustor was designed with a cavity to ensure stable flame holding and six degree area expansion. An ethylene/oxygen igniter was used to ensure stable ignition in the combustor. The main diagnostic techniques used to get a better understanding of the combustor flowfield and operation were static wall pressure measurements, broadband luminescence, schlieren imaging, and two-point focused laser differential interferometry velocimetry. In the initial baseline case, single injection was studied across different combustor equivalence ratios, or ϕ . In the distributed fuel injection cases, total combustor equivalence ratio was maintained constant while the number of injectors used was varied. In the active control experiments, fast-response solenoids were used to switch between different injection schemes in a single test run. The key results from these experiments

were:

- As the combustor equivalence ratio was increased in the single injection case, the static wall pressure profile as well as the imaging obtained indicated at certain ϕ , the combustor operated in thermally choked mode. Thermally choked mode was characterized with a strong pressure peak in the cavity region using the wall pressure data, and normal shock train formation in the combustor in the imaging diagnostics. Supersonic combustion, however, was characterized as a gradual pressure rise in the combustor and an oblique shock train formation in the isolator/combustor. The single injection experiments started from a no injection case to a ϕ of 0.73 case. The ϕ of 0.52 case was identified as a strong, thermally choked condition for the single injection and was used as a comparison for the distributed injection cases. The ϕ of 0.2 single injection case was identified as a supersonic combustion case and chosen as the fueling condition for the pilot flame in the distributed injection cases.
- In the distributed fuel cases, supersonic combustion was observed when a ϕ of 0.52 was injected. The pressure profiles indicated a gradual pressure rise as opposed to a large pressure spike seen in thermally choked mode operation. Furthermore, the imaging data confirmed the formation of a supersonic oblique shock train formation in the combustor during operation. A blended fuel mixture of methane and hydrogen of a ϕ of 0.47 was also injected using the distributed fuel injection scheme which exhibited a similar pressure trend as the pure hydrogen injection distributed injection scheme indicating supersonic combustion. Therefore, by using distributed injection, premature thermal choking was avoided.

- The heat release profile in the combustor is shown to be directly related to the number of injectors used. This is confirmed with the deduced heat release model developed using experimental data and quasi one-dimensional analysis. The single injection case at a ϕ of 0.52 was shown to have most of its heat release occurring in the cavity while the distributed injection case at a ϕ of 0.52 exhibited a gradual heat release across the entire combustor. The relatively large heat release in the smaller, confined area in the single injection case led to premature thermal choking. In the distributed injection case, heat is added to expanding portions of the combustor, so more heat can be added before the flow chokes.
- Deduced velocity obtained from experimental measurements and Rayleigh flow analysis is compared to non-intrusive velocity measurements obtained experimentally using a two-point focused laser differential interferometry. In both the deduced velocities and the experimentally obtained velocities, the trend of the data agrees well with the known physical characteristics of the flow fields. In the single injection case, the flow is observed to choke in the cavity region and expand back to supersonic speeds downstream of the combustor before boundary layer separation occurs and the velocity sharply decreases. In the supersonic case, the flow remains supersonic throughout. The deduced and 2pFLDI velocity data both reflect these trends. Furthermore, the independently obtained deduced velocity and 2pFLDI velocity have some overlap across a number of data points further adding confidence to both techniques.
- The active control tests demonstrated the ability to switch between supersonic combustion and thermally choked mode operation by actively controlling fuel injection distribution through the use of fast-response solenoid valves. The transition was shown to occur on the

order 1 ms. Furthermore, bi-directional control of mode transition was exhibited by being able to switch back and forth between stable thermally-choked mode and stable supersonic combustion mode.

7.1 Key Findings

The ability to switch between combustor modes ad hoc in real world flight applications is critical for different specific flight scenarios. Actively controlled combustor mode transition, with timescales on the order of 1ms, is found to be much faster than natural combustor mode transition, which is reported to be on the order of 500 ms. As such, not only does active control allow for rapid transition between modes, it contributes to the overall stability of the engine. The longer timescales associated with natural combustor mode transition is associated with greater likelihood of combustion dynamic events. Moreover, natural combustor mode transition is shown to exhibit frequent mode hopping whereas the active control experiments exhibited a stable, one-way transition.

There are, however, key details to consider when implementing a practical distributed fuel injection system. In this research, fuel was injected normal to the wall and transversely which causes bow shock formation around the injection point. This leads to stagnation pressure losses that may contribute to performance losses. Having multiple transverse injectors like what are used in this study can provide further sources of stagnation pressure loss. At the same time, distributed injectors may reap the benefits of being in the wake of an upstream injector seeing advantages in burning efficiency or penetration height which may prove to outweigh any stagnation pressure deficits. Flameholding methods also need to be considered in tandem with fuel injection schemes.

In all cases tested, fuel was only observed to ignite when reaching the cavity-stabilized flame except for rare instances where the flame briefly stabilized behind the wake of a fuel injector. Therefore, optimization and overall system consideration is needed when applying a distributed fuel injection system in a real setting, but the principle of using distributed fuel injection as means of controlling mode transition is still very much applicable.

7.2 Scientific Contributions

The reacting flow experiments performed in this research contributed to the scientific field by:

- For the first time, showing a direct comparison between a singular injection scheme and an axial distributed injection scheme as it pertains to combustor behavior.
- Attaining greater understanding of scramjet ignition processes as well as combustor mode transition behavior.
- Demonstrating a previously untested method of actively transitioning between combustor modes at relatively fast timescales.
- Providing new understanding and insights into the actively-forced combustion-mode-transition process between supersonic combustion mode and thermally choked combustion mode.
- Developing a new enabling technique for dealing with potential combustion instability problems in scramjet combustor that can occur during the natural combustor mode transition process.

- Applying for the first time, with support from fellow UMD Researcher, Andrew Ceruzzi, a two point focused laser differential interferometry technique in a high-speed, reacting scramjet flowfield to obtain non-intrusive velocity measurements.

7.3 Future Work

Past research has shown combustor mode transition to have a characteristic frequency and an associated large pressure spike. How the dynamic pressure spectra reacts to an actively controlled mode transition remains to be seen and is the subject of future work. The active control sequencing can also be further studied and optimized to make it more feasible in a real-world setting. Furthermore, preliminary results using a blended hydrocarbon fueling condition in the dual-mode scramjet combustor has been attained as well as preliminary formaldehyde PLIF data in a burner setting. Therefore, it would be useful to quantify the heat release for each distribution scheme using the formaldehyde radicals present during combustion, which are early markers of heat release. The ensuing heat release profile can be used to compare to the deduced heat release model attained using a quasi-one dimensional analysis and past experimental data. Application of other velocimetry techniques such as PIV would also be useful to help validate the deduced velocity from the heat release model and the measured non-intrusively obtained velocity from 2pFLDI.

Appendix A: Key Derivations

A.1 Pressure Recovery Analysis

Due to certain entropy generating mechanisms between the heater and the combustor due to shock train formation in the isolator and losses across the nozzle, there is an associated stagnation pressure loss. In order to get a reference estimate of this loss, isentropic relations as shown in Eq. A.1 are used in conjunction with the wall pressure data from Figure 5.1. Gamma was simulated to be 1.287 using a Cantera model and the vitiated flow properties. Furthermore, the strongest pressure rise is observed in the single injection/thermally choked case where the flow is known to reach Mach 1 in the cavity.

$$\frac{P}{P_0} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-\gamma}{\gamma - 1}} \quad (\text{A.1})$$

From Eq. A.1, the expected ratio of static pressure to stagnation pressure at the point of thermal choking is calculated to be 0.548, whereas the ratio of static pressure to stagnation pressure depicted in Figure 5.1 is measured to be approximately 0.302. This indicates that approximately 55% of the total pressure is recovered from the vitiated heater exit to the point of thermal choking for the strong thermal choking case.

A.2 Heat Release Deduction

A.2.1 Isolator Exit/Combustor Entrance Conditions

To establish the combustor entrance conditions or the boundary conditions used to deduce the heat release, a combination of one-dimensional analysis and experimental data was used. The flow exiting the vitiated heater enters a half-nozzle which expands the flow to Mach 2 speeds before the flow enters the isolator. The centerline, stagnation temperature as well as the stagnation pressure before the nozzle were measured. The flow through the vitiated heater has a distinct profile akin to pipe as seen in past data shown in Figure 4.2. Therefore, using this data, a bulk temperature is found and can be used in the heat release calculations. Using this information along with the known nozzle geometry, the mass flow rate can be calculated as shown in Eq. A.2.

$$\dot{m} = \frac{A * P_0}{\sqrt{T_o}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (\text{A.2})$$

Since there is no mass addition in the isolator, the mass flow rate can be assumed to be constant throughout it. Therefore, at the isolator exit a relationship between Mach number, stagnation pressure, and stagnation temperature can be established as shown in Eq. A.3.

$$\dot{m} = \frac{A * P_0}{\sqrt{T_o}} \sqrt{\frac{\gamma}{R}} M \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad (\text{A.3})$$

Stagnation temperature can also be assumed constant in the isolator as there is no mechanism for heat gain/loss. Stagnation pressure, however, cannot be assumed to be constant as there are entropy generating mechanisms in the isolator such as the shock train formation. The static

wall pressure measurement at the end of the isolator. Using isentropic relations, the local Mach number can be represented as a function of the local stagnation pressure and local static pressure as seen in Eq. A.4.

$$M = \sqrt{\left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} \frac{2}{\gamma-1}} \quad (\text{A.4})$$

Therefore, Eq. A.3 can be re-written using Eq. A.4 with the only unknown being stagnation pressure and solved for implicitly.

A.2.2 Combustor Calculations

By using a combination of theoretical analysis, experimental pressure, and temperature data, a heat release profile can be obtained. The analysis was performed step-by-step along the length of the combustor. In the single injection case, it is assumed that the flow is thermally choked at $x/H = 2$ as can be visually inferred from the images obtained and past data.

Each point consisted of six steps of analysis. The first step was to consider the theoretical effect of combustor area expansion without heat addition on the flow Mach number using quasi-one dimensional analysis as shown by

$$\frac{A_1}{A_2} = \frac{M_2}{M_1} * \frac{\left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{(\gamma+1)}{2(\gamma-1)}}}{\left(1 + \frac{\gamma-1}{2} M_2^2\right)} \quad (\text{A.5})$$

where M_2 is implicitly solved for using the known area expansion and ratio of specific heats.

The next step involves using isentropic relations, the Mach number determined in the previous step, and the experimentally obtained stagnation pressure to calculate the corresponding

theoretical static pressure of the flow as given by

$$P = \frac{P_o}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}} \quad (\text{A.6})$$

Next, the effect of heat addition was considered through the application of Rayleigh flow analysis. The Mach number change due to heat addition is determined as the pressure change from the theoretical static pressure attained from Eq. A.6 and the experimentally attained wall pressure data as shown by

$$M = \sqrt{\frac{1}{\gamma} \left[\frac{P_1}{P_2} (1 + \gamma M_1^2) - 1 \right]} \quad (\text{A.7})$$

Then, the corresponding stagnation temperature change can then be determined using the Mach number attained from Eq. A.7 using

$$T_{02} = T_{01} \left(\frac{1 + \gamma M_1^2}{1 + \gamma M_2^2} \right)^2 \left(\frac{M_2}{M_1} \right)^2 \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_1^2} \right) \quad (\text{A.8})$$

As heat is added to the flow, the stagnation pressure of the flow correspondingly drops. The updated stagnation pressure to be used in the next iteration of the calculation is found using

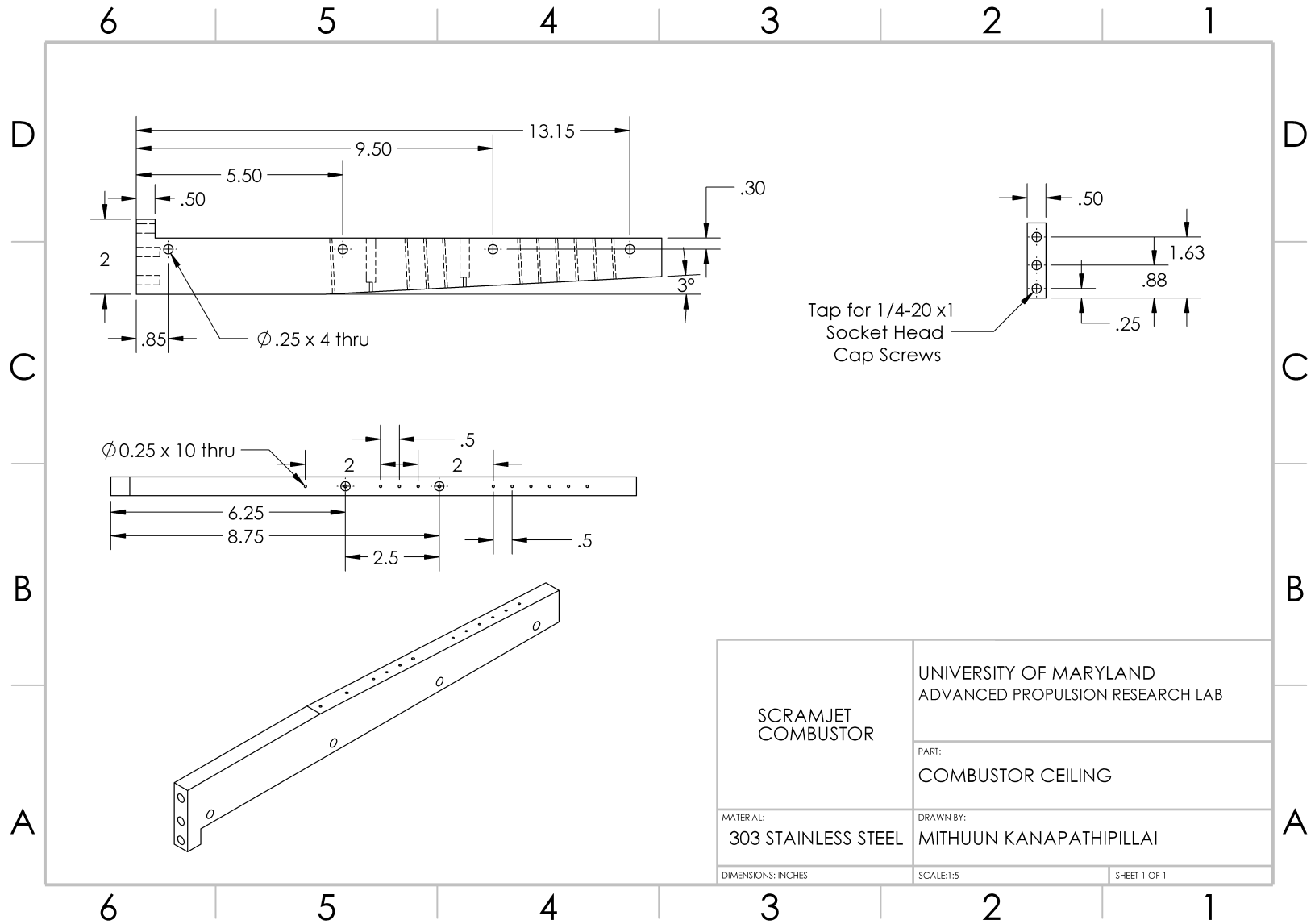
$$P_{02} = P_{01} \left[\frac{1 + \gamma M_1^2}{1 + \gamma M_2^2} \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma}{\gamma-1}} \right] \quad (\text{A.9})$$

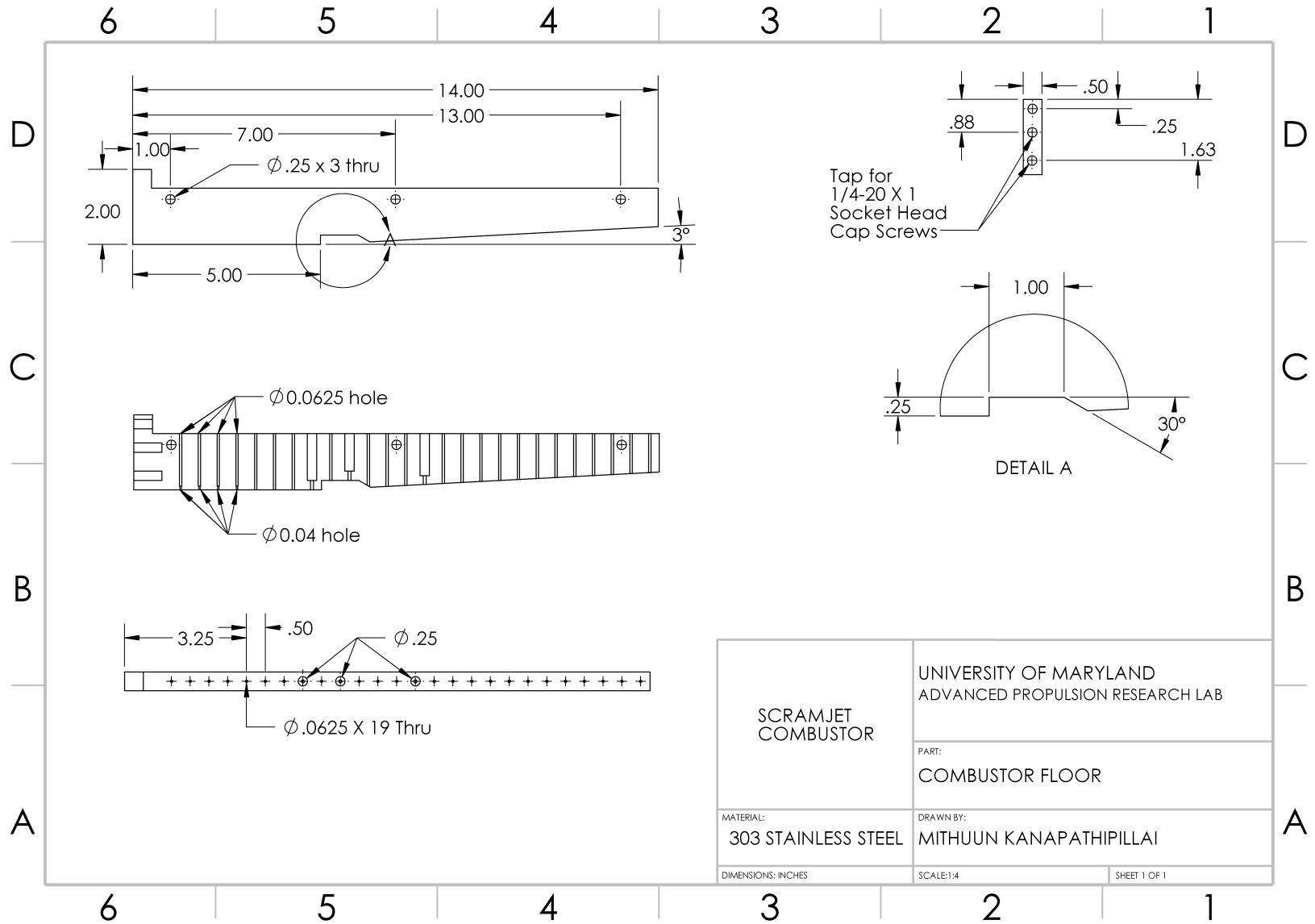
Finally, the heat per unit mass can be estimated using

$$q = C_p (T_{02} - T_{01}) \quad (\text{A.10})$$

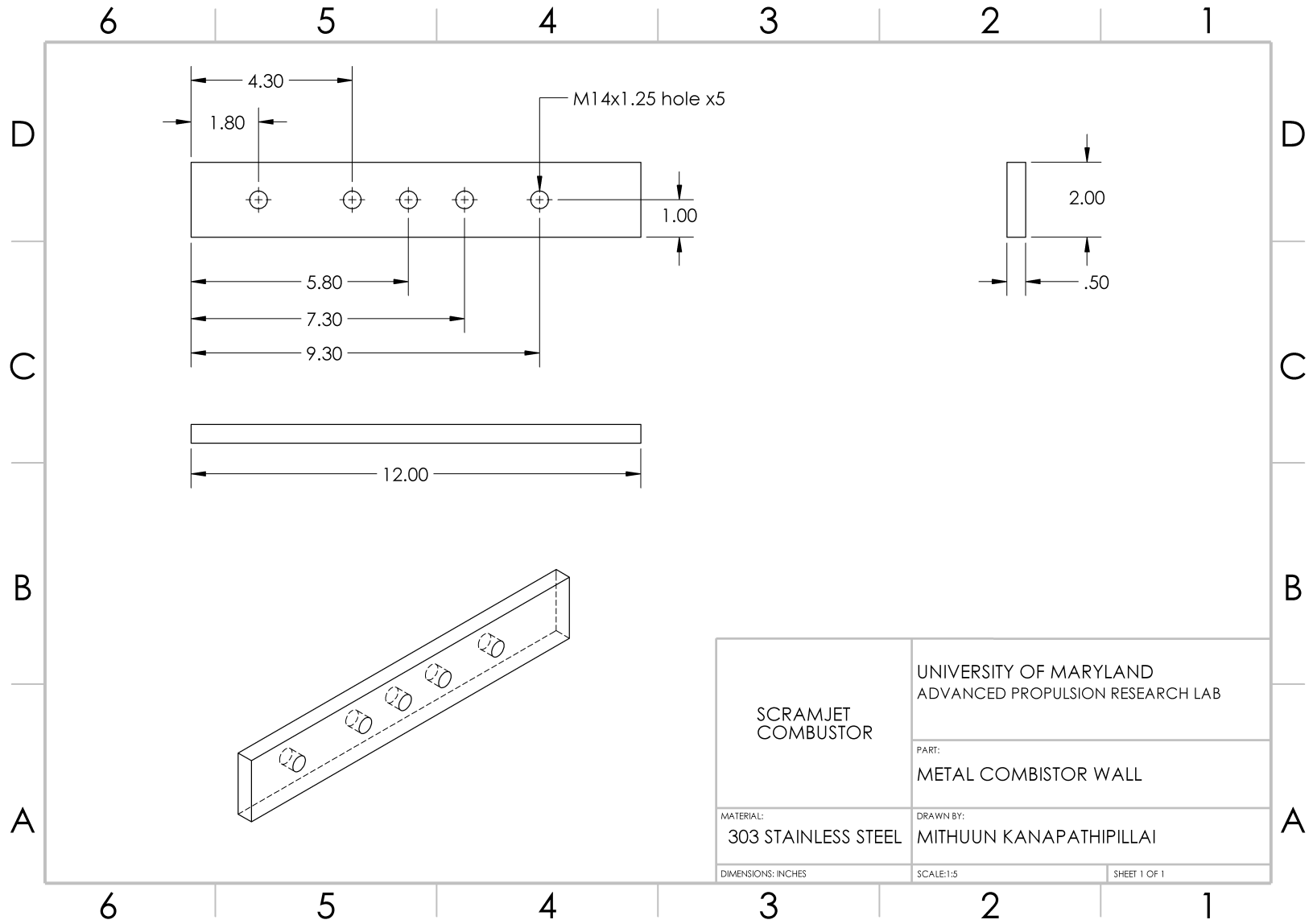
Appendix B: Key Drawings

This section includes pertinent drawings of the dual-mode scramjet combustor rig used for the distributed fuel injection tests. The dimensions for all drawings are presented in inches.





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Appendix C: Future Work: Preliminary Results

In real-life applications, hydrocarbon fuel would be considered a more practical fuel of choice. Preliminary results have been obtained using a distributed fuel injection setup with gaseous methane. This opens up the possibility of applying different diagnostic techniques that take advantage of hydrocarbon combustion. Specifically, a Formaldehyde PLIF technique can be applied to attain heat release information in the combustor and to better characterize the effect of fuel distribution on heat release.

C.1 Formaldehyde PLIF

Formaldehyde products have been found to be an early marker of heat release in hydrocarbon combustion [48]. Through excitation of the formaldehyde molecule, different information about the flame structure and position can be obtained from the corresponding emitted fluorescence [49].

C.2 Distributed Hydrocarbon Injection

Preliminary results were obtained with methane in the distributed injection setting. Due to the longer ignition delay times associated with methane, a pilot flame fueled by hydrogen at a ϕ of 0.20 was established for the methane cases. Figure C.1 compares the single injection

cases fueled by hydrogen fuel only to a distributed case with a methane-hydrogen fuel mixture for a total blended equivalence ratio of 0.47. The disparity between the blended fuel mixture can be observed in Figure C.2 where the methane burns blue as it comes out of injector # 3. The ϕ of 0.47 case through injector 1 only should be a strong thermally-choked case based on the data from Chapter 4 and the single injection cases presented in Figure C.1. The blended-fuel distributed case, however, indicates that thermal choking is still delayed and is operating in supersonic combustion mode as the pressure trace resembles the hydrogen-fueled distributed injection cases presented earlier. Therefore, despite altering the fuel choice, distributed fuel injection is still a viable method of controlling combustor mode operation, which is consistent with the fact that combustor mode transition is a function of the heat release in the combustor.

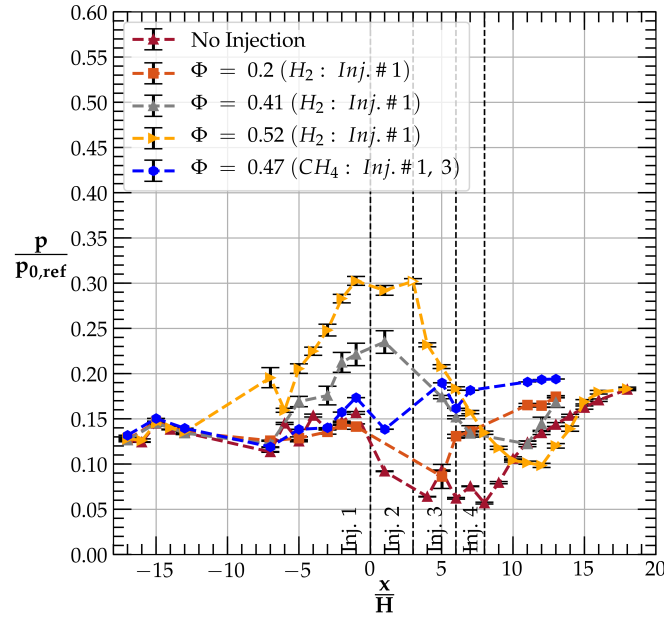


Figure C.1: Combustor and isolator wall pressure distributions for hydrogen-fueled single injection and methane-fueled cases.

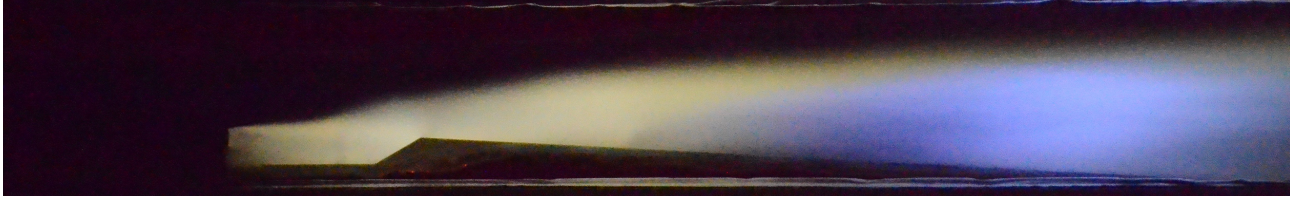


Figure C.2: Broadband luminescence of blended-hydrocarbon fuel distributed injection combustion

C.3 Burner

Preliminary results were obtained in a methane-power burner. Typical burner operation is shown in Figure C.3. Formaldehyde PLIF was performed with a 355-nm frequency-tripled ND:Yag laser ran at 10 Hz used to excite the formaldehyde particles in the flame. The resulting image obtained is shown in Figure C.4. The next stage would be to apply the FPLIF technique in the blended fuel distributed injection cases in the scramjet rig to further understanding of how fuel distribution can affect heat release.



Figure C.3: Zoomed image of typical burner operation.

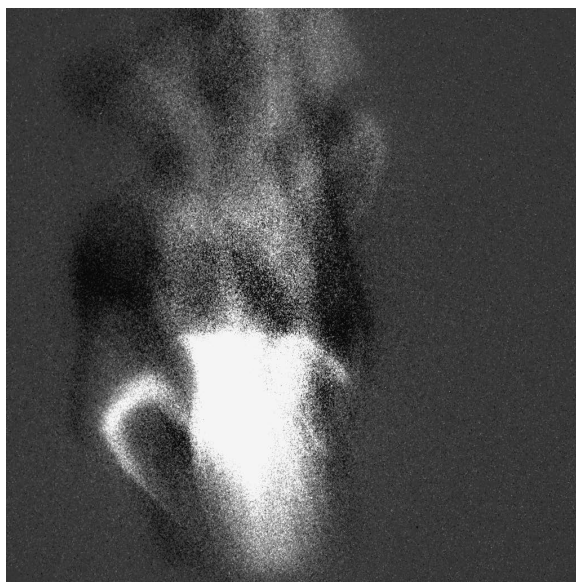


Figure C.4: Formaldehyde PLIF image of a diffusive methane flame

Appendix D: Pressure Data

This section provides the pressure response of the individual pressure ports during the test's runtime for different cases.

D.1 Static Wall Pressure Measurement Change

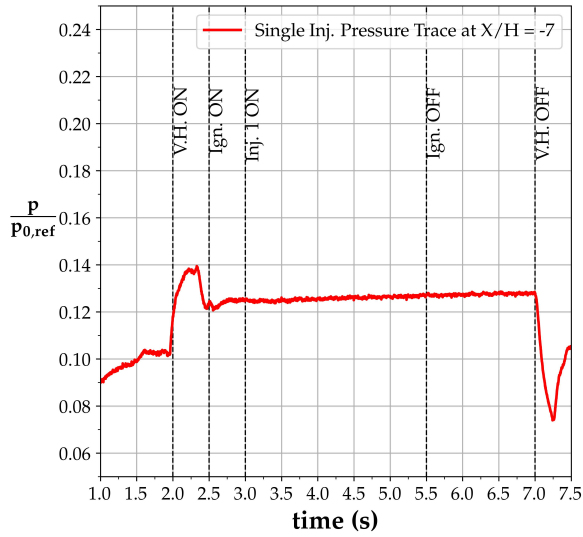


Figure D.1: Pressure evolution for static wall pressure measurement at $x/H = -17$ for single injection

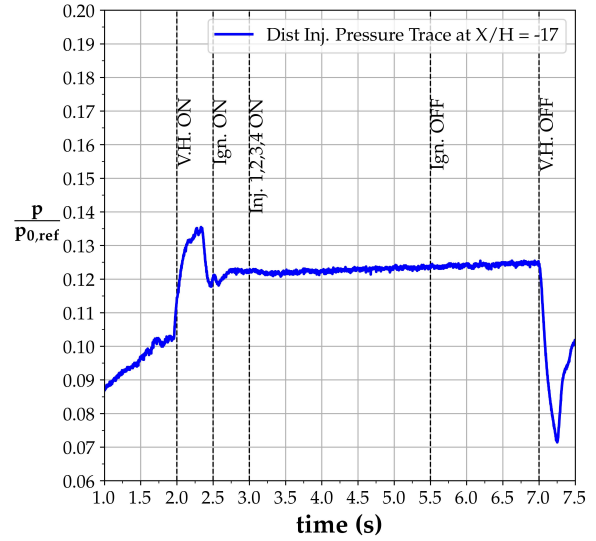


Figure D.2: Pressure evolution for static wall pressure measurement at $x/H = -17$ for distributed injection.

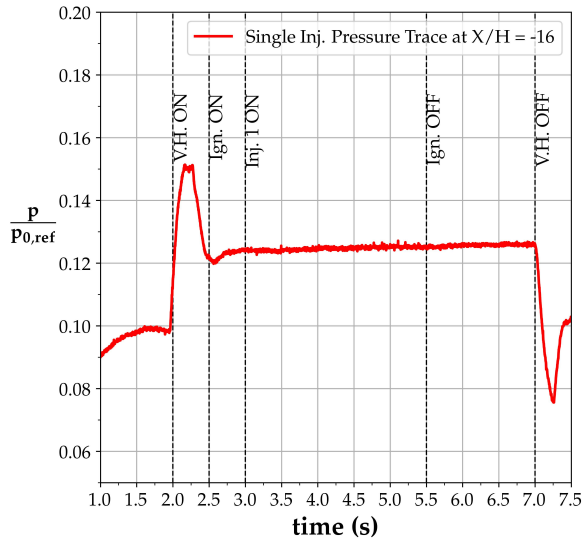


Figure D.3: Pressure evolution for static wall pressure measurement at $x/H = -16$ for single injection

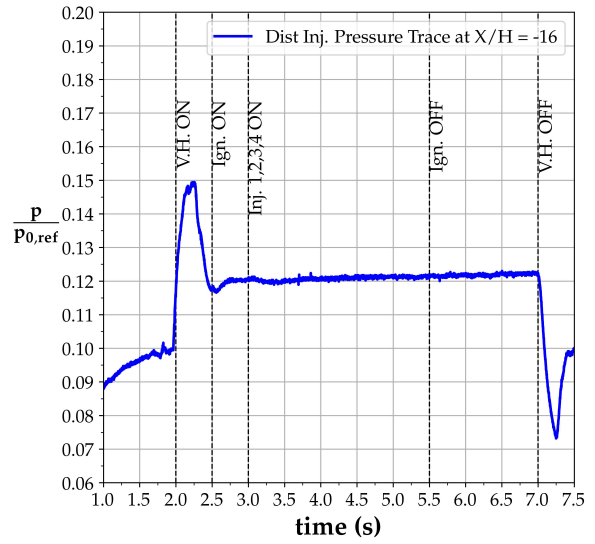


Figure D.4: Pressure evolution for static wall pressure measurement at $x/H = -16$ for distributed injection.

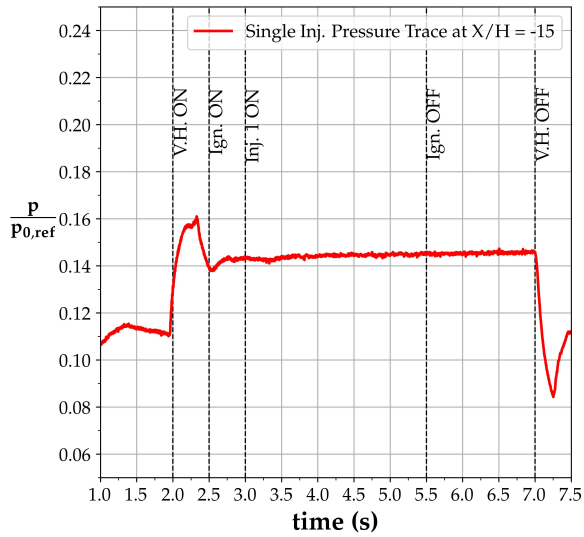


Figure D.5: Pressure evolution for static wall pressure measurement at $x/H = -15$ for single injection

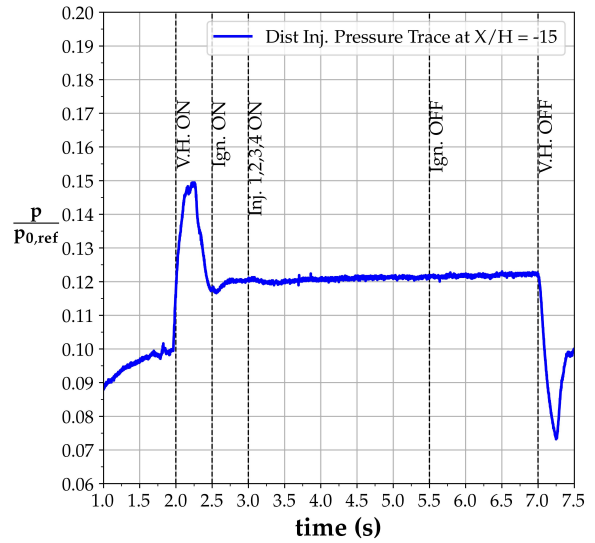


Figure D.6: Pressure evolution for static wall pressure measurement at $x/H = -15$ for distributed injection.

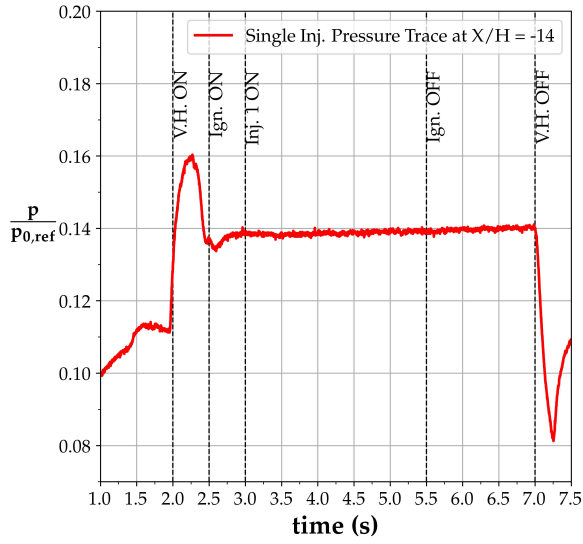


Figure D.7: Pressure evolution for static wall pressure measurement at $x/H = -14$ for single injection

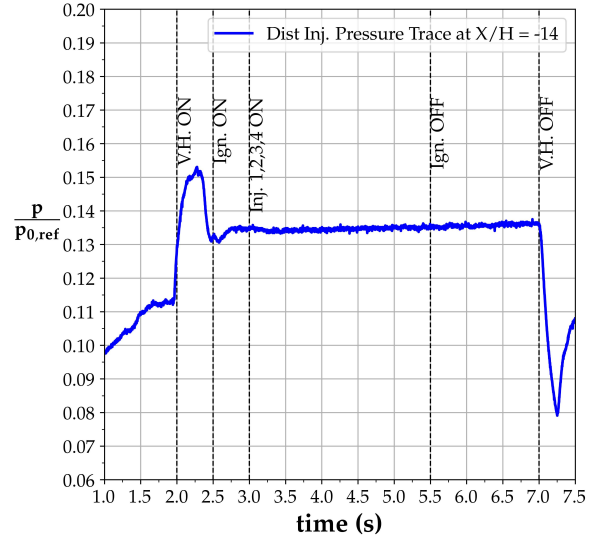


Figure D.8: Pressure evolution for static wall pressure measurement at $x/H = -14$ for distributed injection.

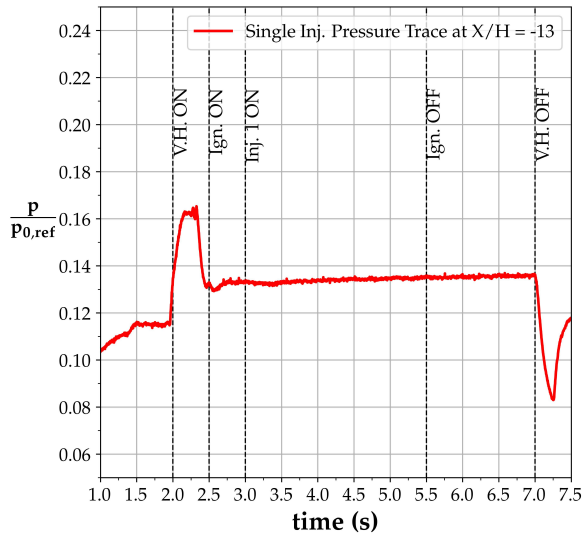


Figure D.9: Pressure evolution for static wall pressure measurement at $x/H = -13$ for single injection

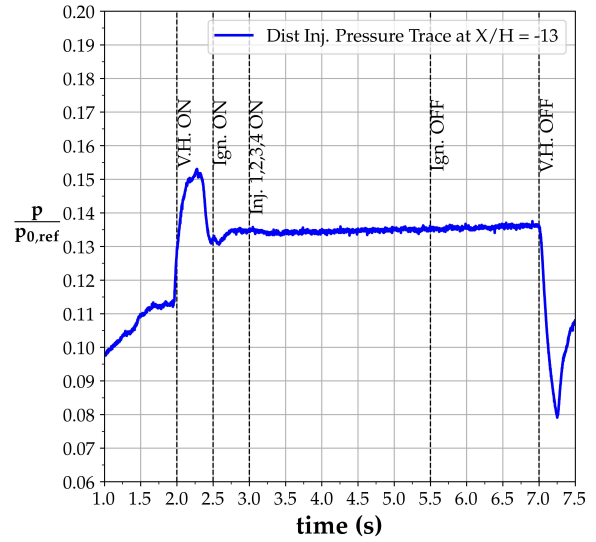


Figure D.10: Pressure evolution for static wall pressure measurement at $x/H = -13$ for distributed injection.

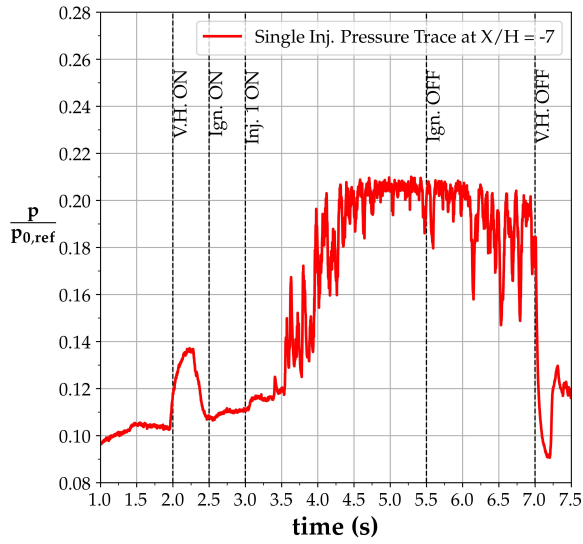


Figure D.11: Pressure evolution for static wall pressure measurement at $x/H = -7$ for single injection

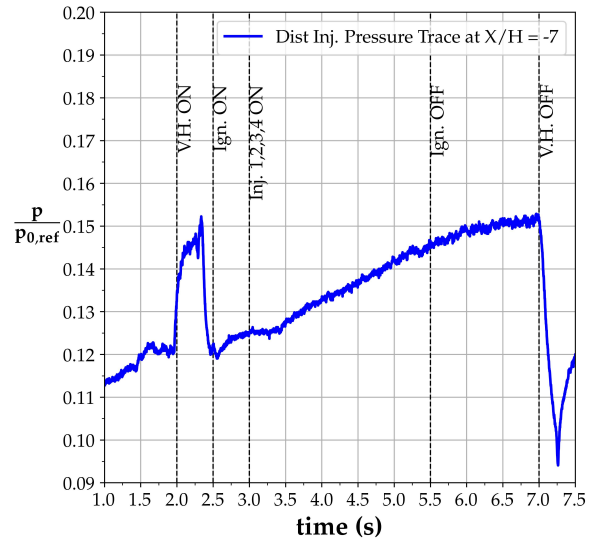


Figure D.12: Pressure evolution for static wall pressure measurement at $x/H = -7$ for distributed injection.

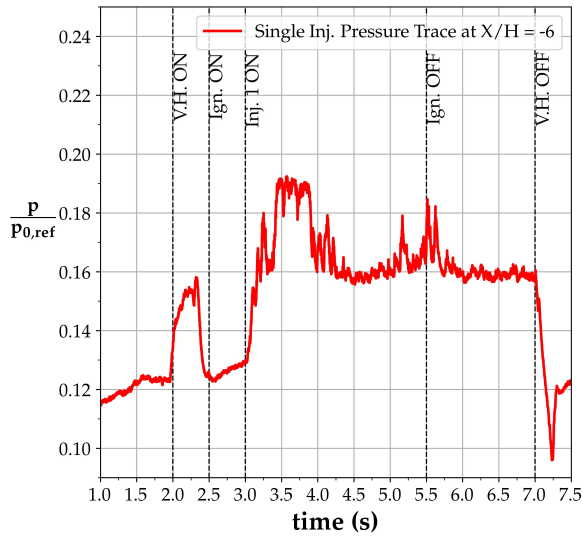


Figure D.13: Pressure evolution for static wall pressure measurement at $x/H = -6$ for single injection

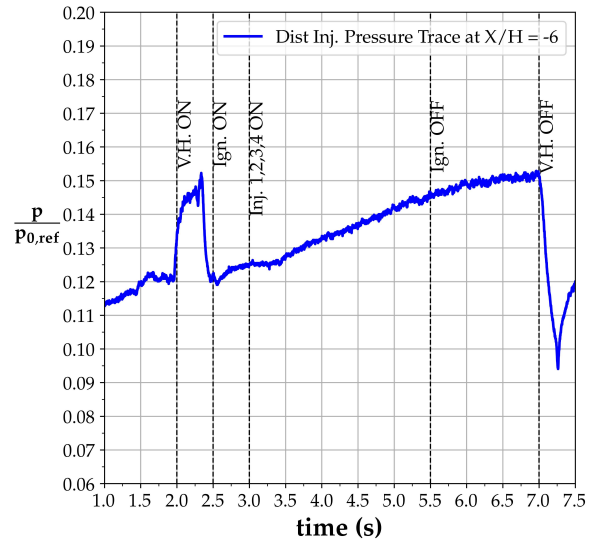


Figure D.14: Pressure evolution for static wall pressure measurement at $x/H = -6$ for distributed injection.

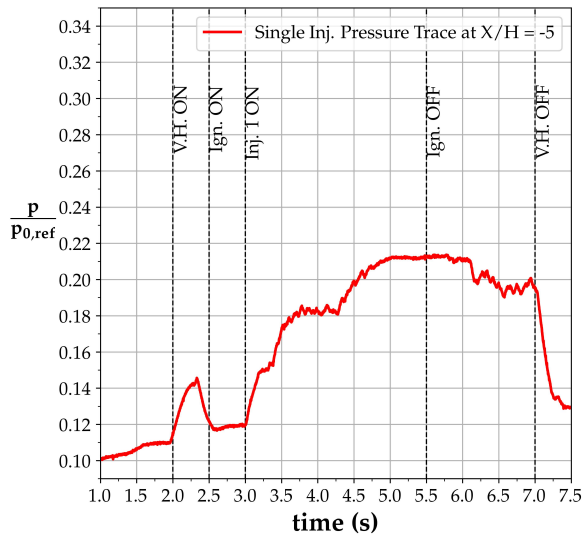


Figure D.15: Pressure evolution for static wall pressure measurement at $x/H = -5$ for single injection

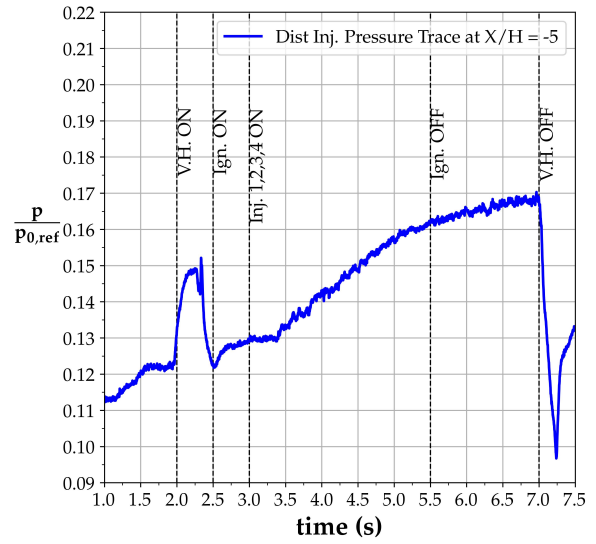


Figure D.16: Pressure evolution for static wall pressure measurement at $x/H = -5$ for distributed injection.

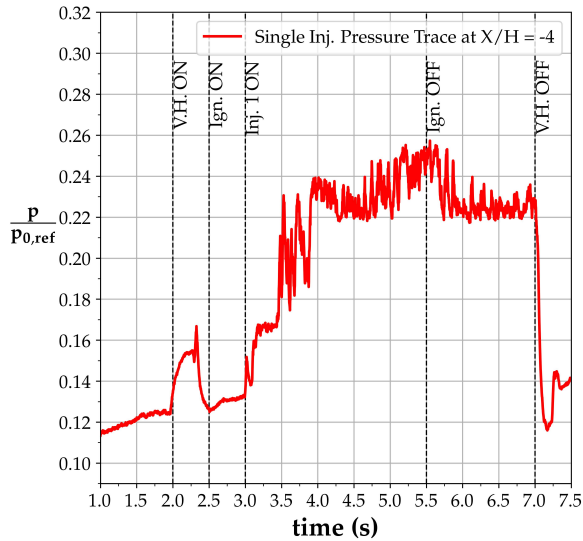


Figure D.17: Pressure evolution for static wall pressure measurement at $x/H = -4$ for single injection

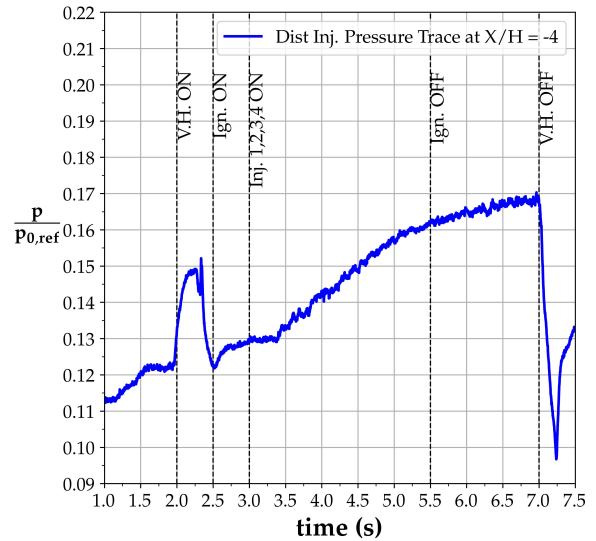


Figure D.18: Pressure evolution for static wall pressure measurement at $x/H = -4$ for distributed injection.

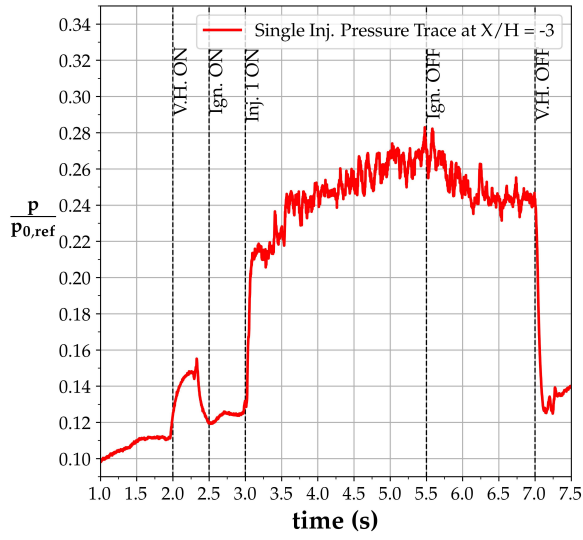


Figure D.19: Pressure evolution for static wall pressure measurement at $x/H = -3$ for single injection

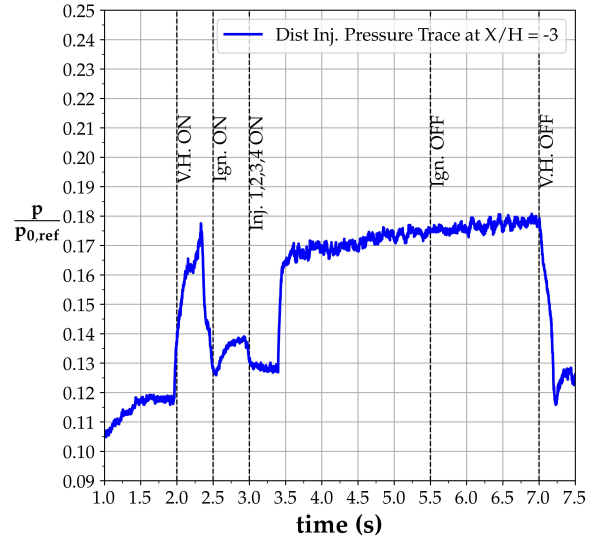


Figure D.20: Pressure evolution for static wall pressure measurement at $x/H = -3$ for distributed injection.

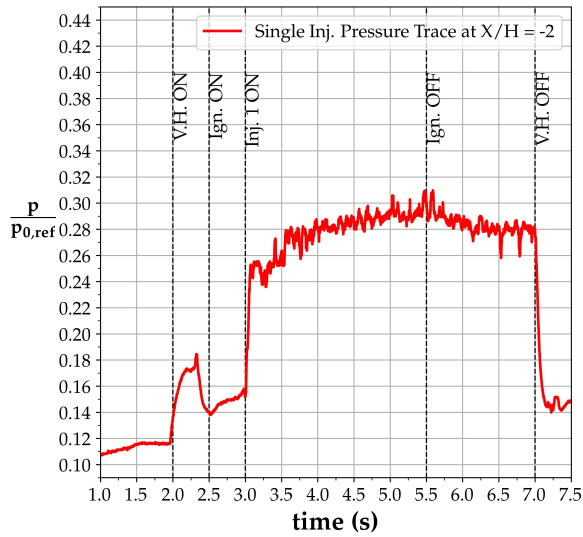


Figure D.21: Pressure evolution for static wall pressure measurement at $x/H = -2$ for single injection

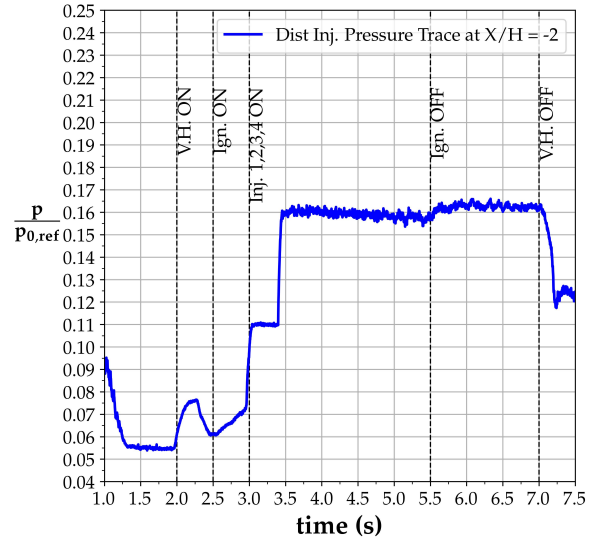


Figure D.22: Pressure evolution for static wall pressure measurement at $x/H = -2$ for distributed injection.

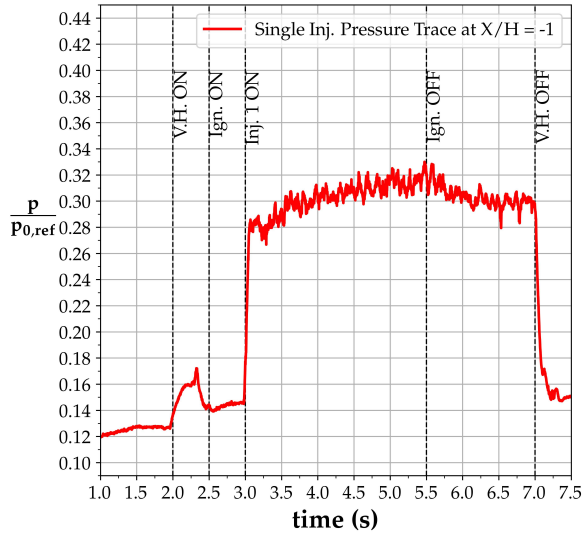


Figure D.23: Pressure evolution for static wall pressure measurement at $x/H = -1$ for single injection

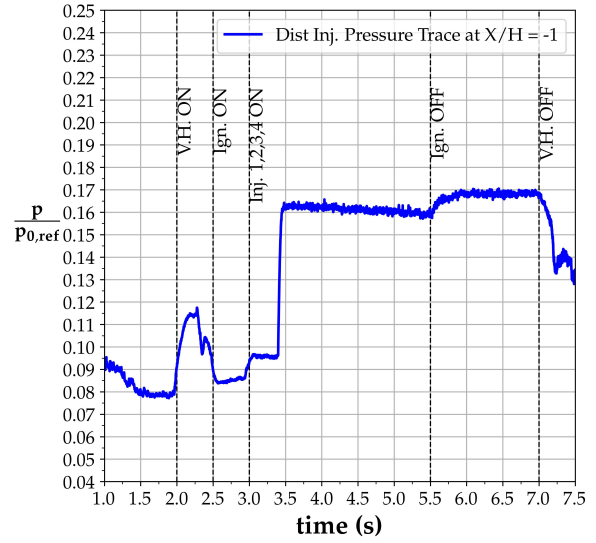


Figure D.24: Pressure evolution for static wall pressure measurement at $x/H = -1$ for distributed injection.

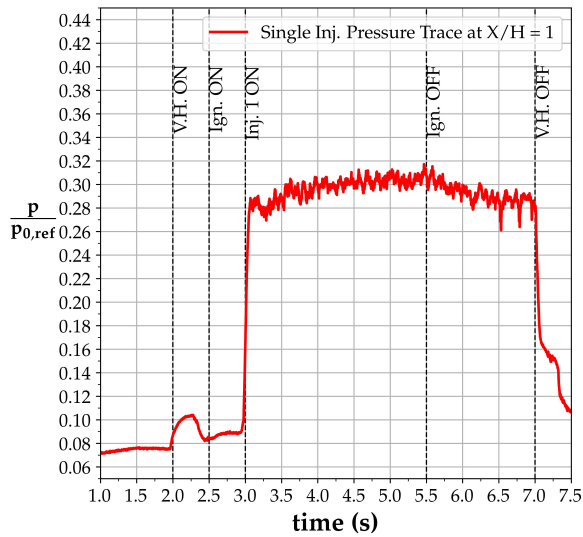


Figure D.25: Pressure evolution for static wall pressure measurement at $x/H = 1$ (bottom port) for single injection

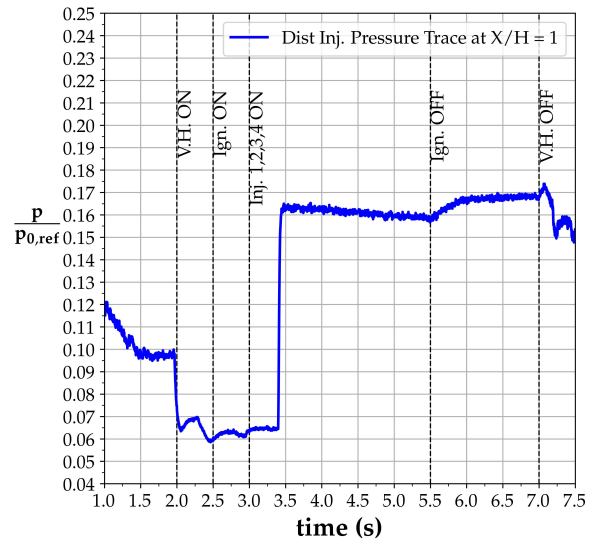


Figure D.26: Pressure evolution for static wall pressure measurement at $x/H = 1$ (bottom port) for distributed injection.

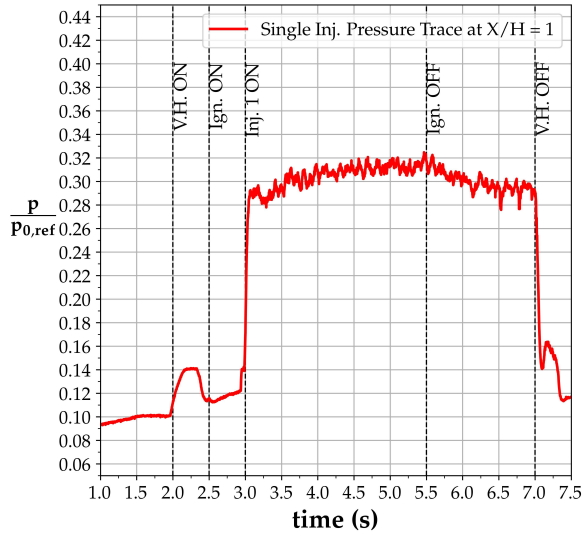


Figure D.27: Pressure evolution for static wall pressure measurement at $x/H = 1$ (top port) for single injection

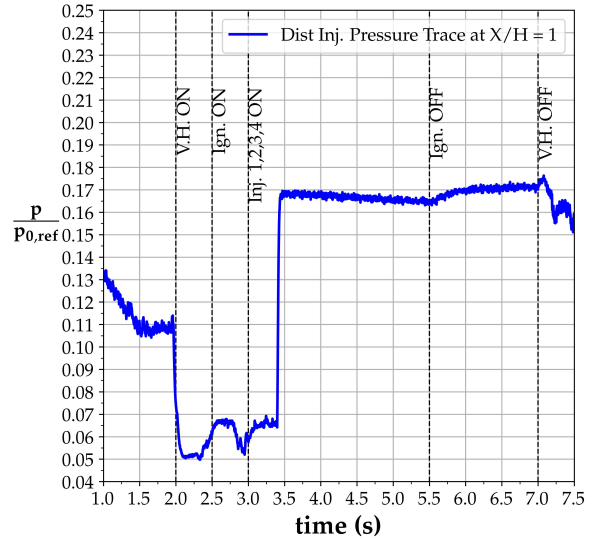


Figure D.28: Pressure evolution for static wall pressure measurement at $x/H = 1$ (top port) for distributed injection.

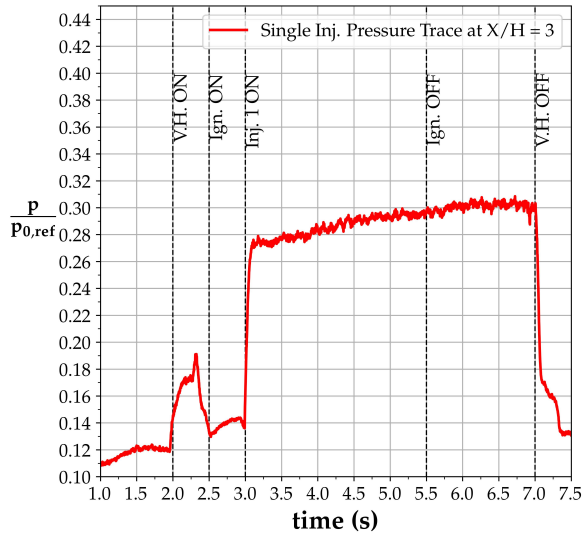


Figure D.29: Pressure evolution for static wall pressure measurement at $x/H = 3$ for single injection

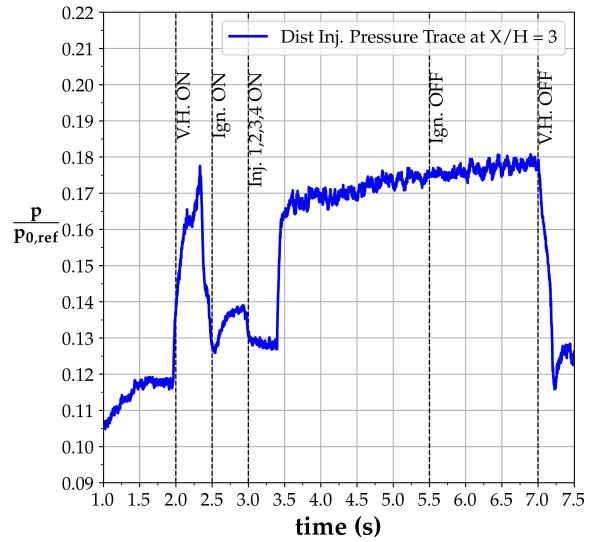


Figure D.30: Pressure evolution for static wall pressure measurement at $x/H = 3$ for distributed injection.

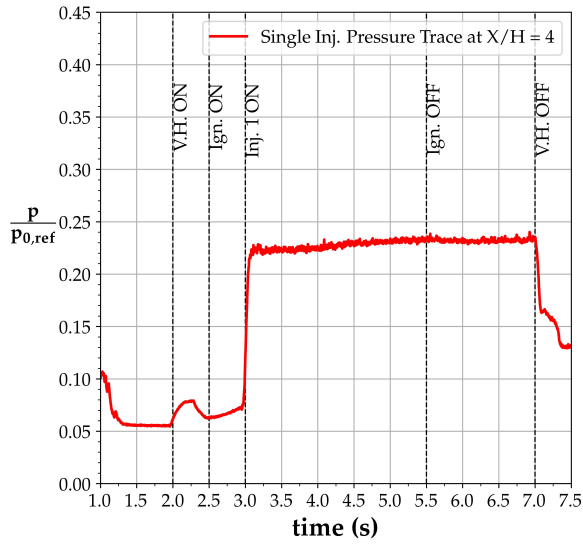


Figure D.31: Pressure evolution for static wall pressure measurement at $x/H = 4$ for single injection

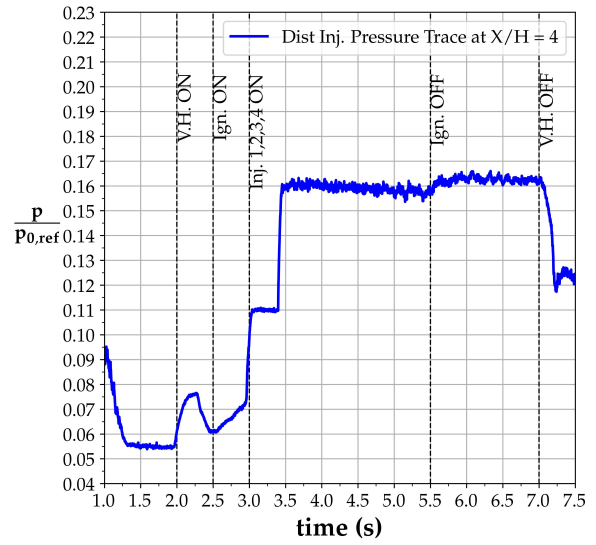


Figure D.32: Pressure evolution for static wall pressure measurement at $x/H = 4$ for distributed injection.

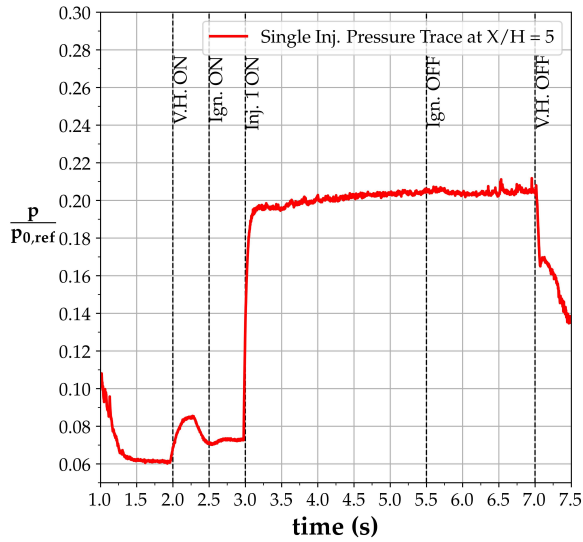


Figure D.33: Pressure evolution for static wall pressure measurement at $x/H = 5$ (top port) for single injection

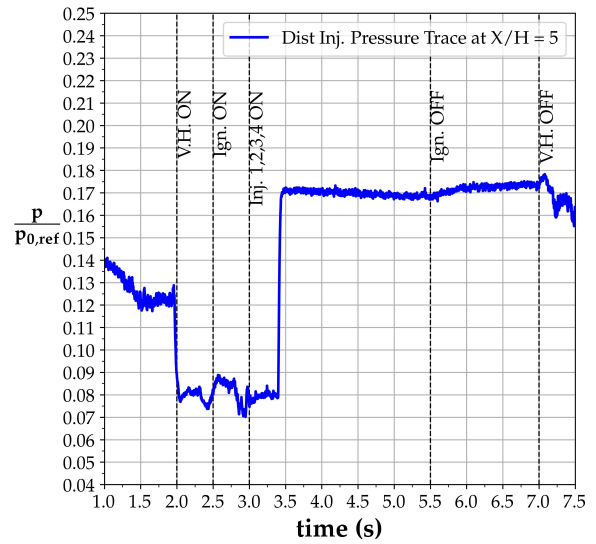


Figure D.34: Pressure evolution for static wall pressure measurement at $x/H = 5$ (top port) for distributed injection.

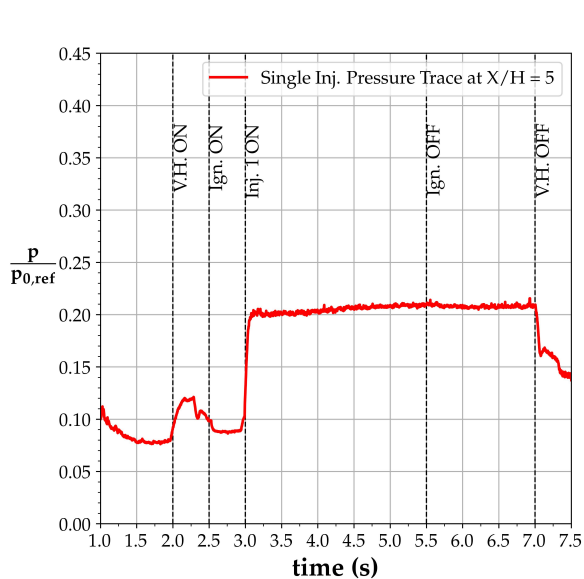


Figure D.35: Pressure evolution for static wall pressure measurement at $x/H = 5$ (bottom port) for single injection

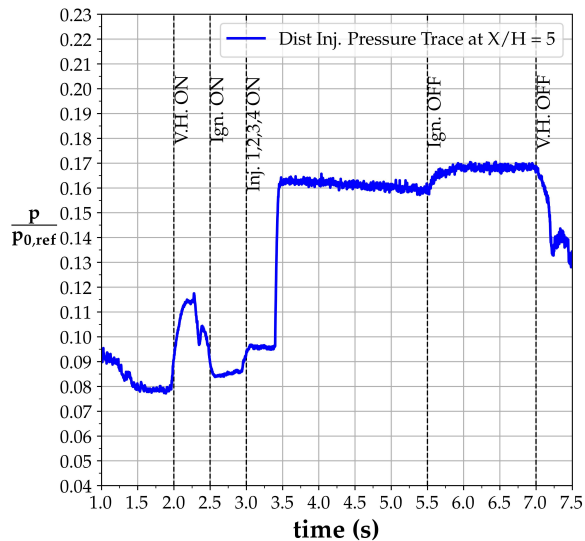


Figure D.36: Pressure evolution for static wall pressure measurement at $x/H = 5$ (bottom port) for distributed injection.

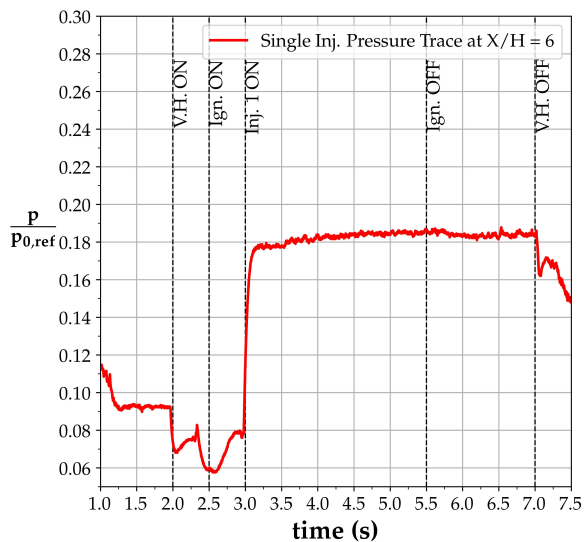


Figure D.37: Pressure evolution for static wall pressure measurement at $x/H = 6$ for single injection

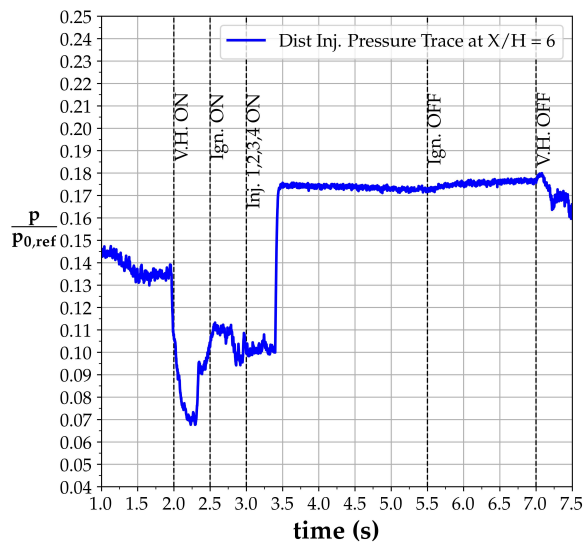


Figure D.38: Pressure evolution for static wall pressure measurement at $x/H = 6$ for distributed injection.

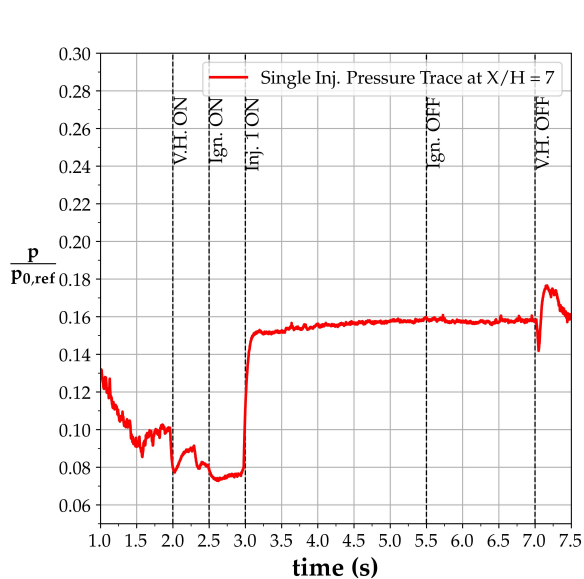


Figure D.39: Pressure evolution for static wall pressure measurement at $x/H = 7$ (top) for single injection

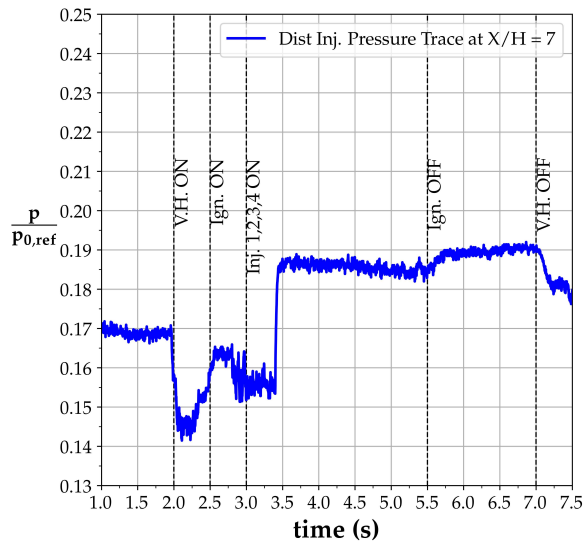


Figure D.40: Pressure evolution for static wall pressure measurement at $x/H = 7$ (top port) for distributed injection.

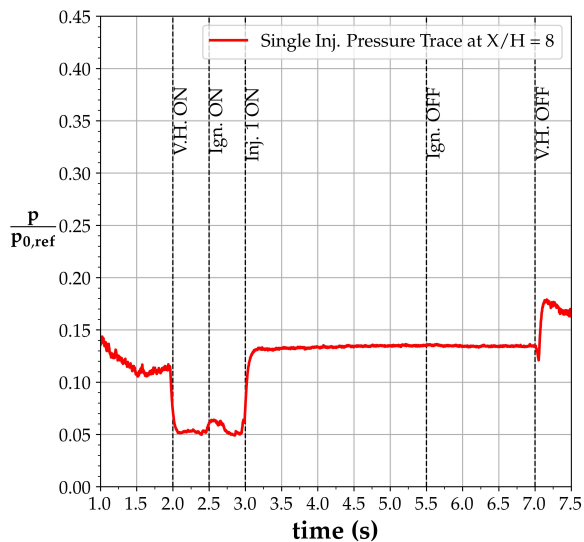


Figure D.41: Pressure evolution for static wall pressure measurement at $x/H = 8$ for single injection

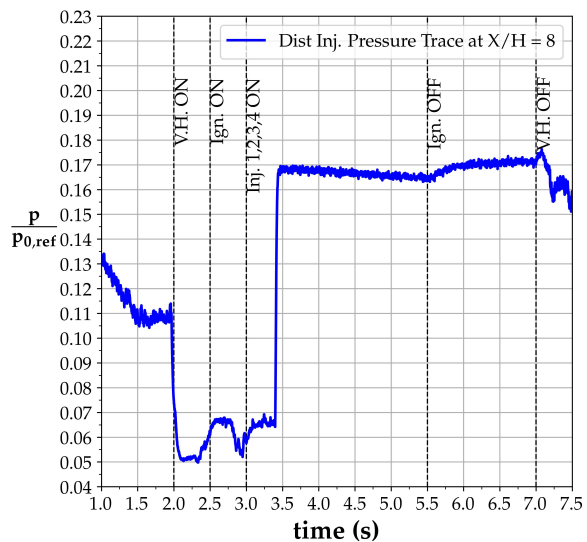


Figure D.42: Pressure evolution for static wall pressure measurement at $x/H = 8$ for distributed injection.

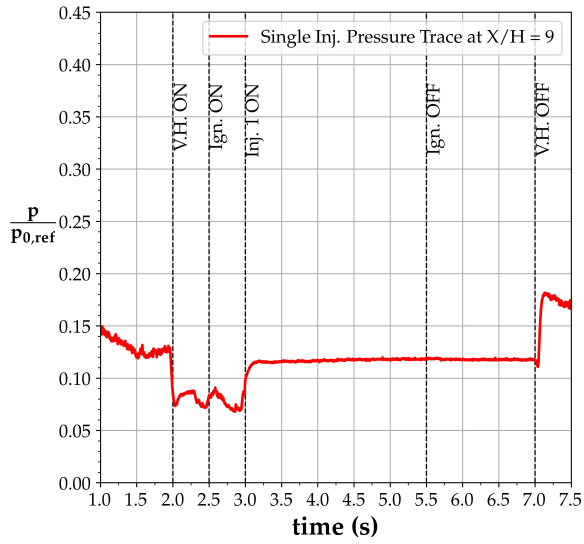


Figure D.43: Pressure evolution for static wall pressure measurement at $x/H = 9$ for single injection

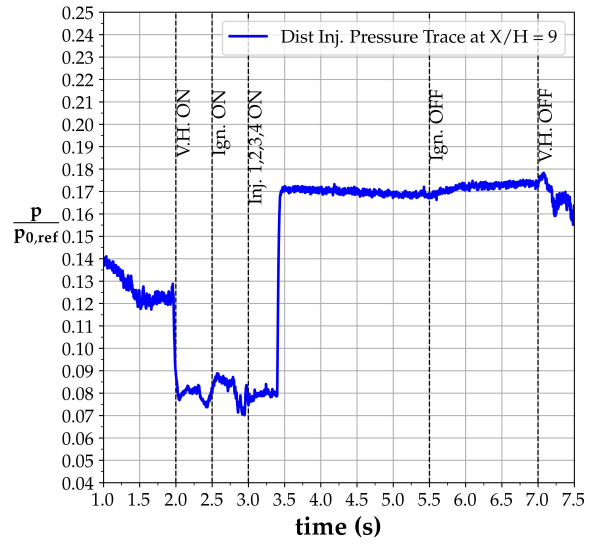


Figure D.44: Pressure evolution for static wall pressure measurement at $x/H = 9$ for distributed injection.

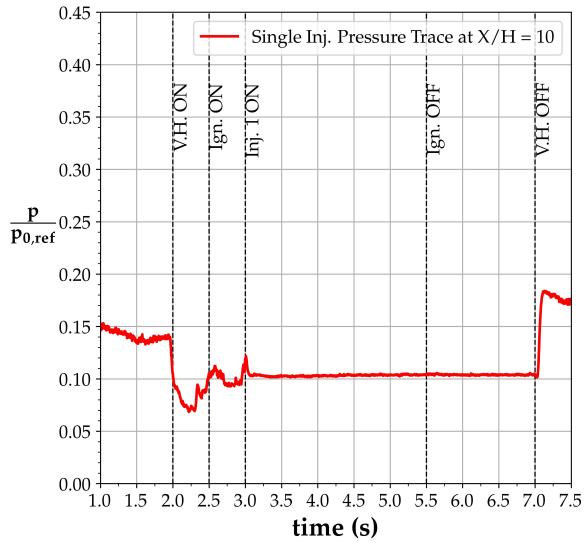


Figure D.45: Pressure evolution for static wall pressure measurement at $x/H = 10$ for single injection

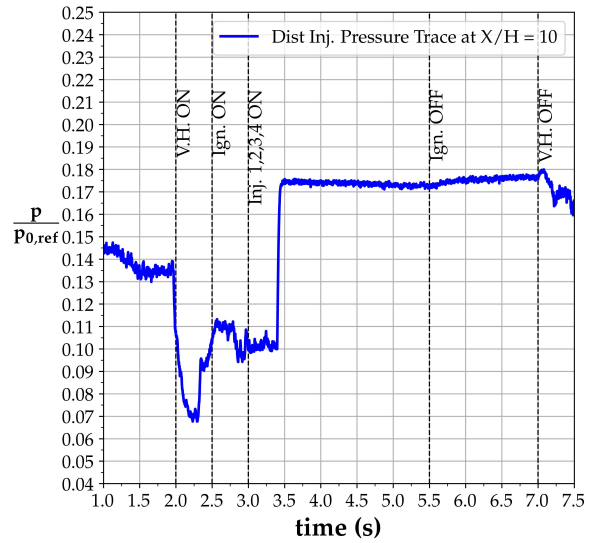


Figure D.46: Pressure evolution for static wall pressure measurement at $x/H = 10$ for distributed injection.

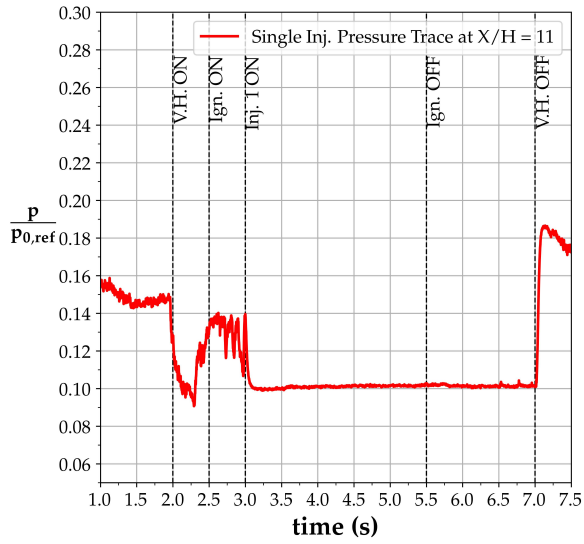


Figure D.47: Pressure evolution for static wall pressure measurement at $x/H = 11$ for single injection

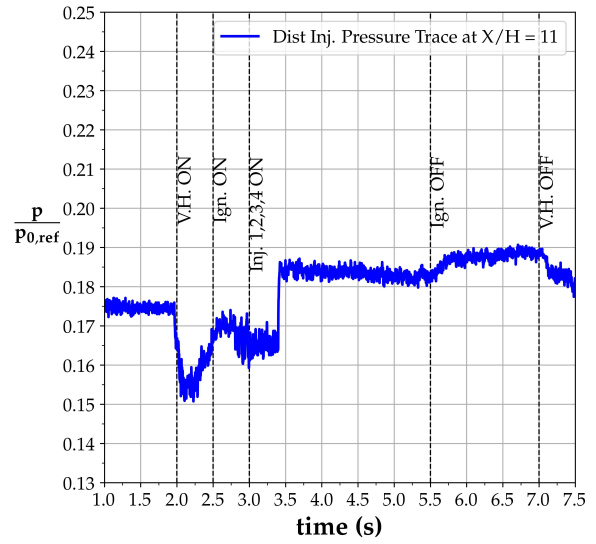


Figure D.48: Pressure evolution for static wall pressure measurement at $x/H = 11$ for distributed injection.

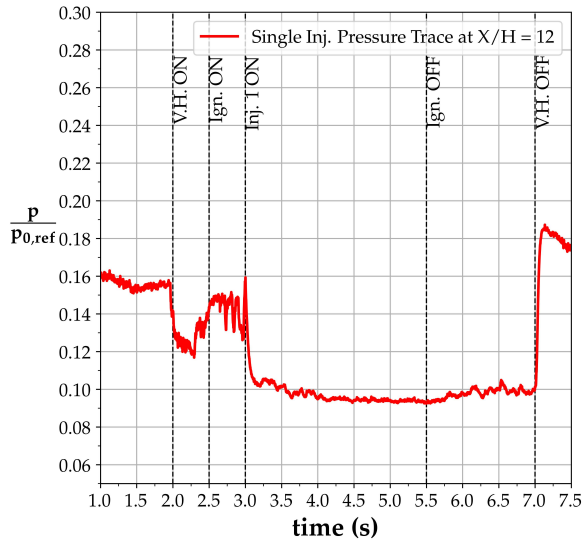


Figure D.49: Pressure evolution for static wall pressure measurement at $x/H = 12$ for single injection

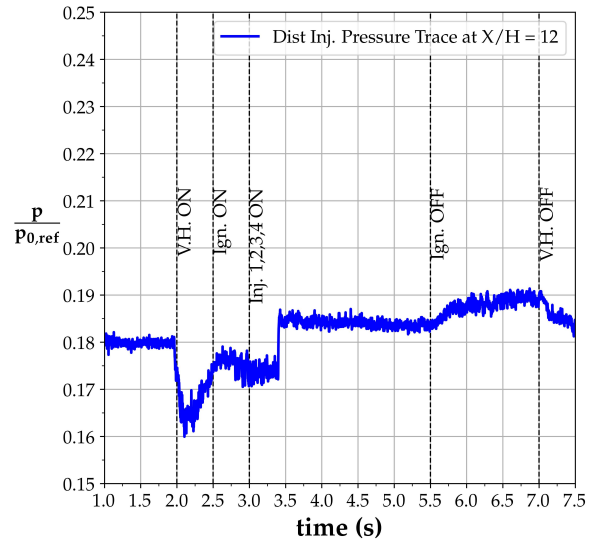


Figure D.50: Pressure evolution for static wall pressure measurement at $x/H = 12$ for distributed injection.

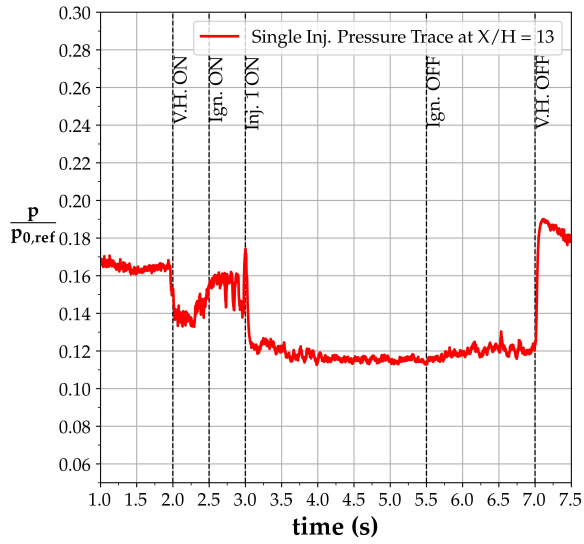


Figure D.51: Pressure evolution for static wall pressure measurement at $x/H = 13$ for single injection

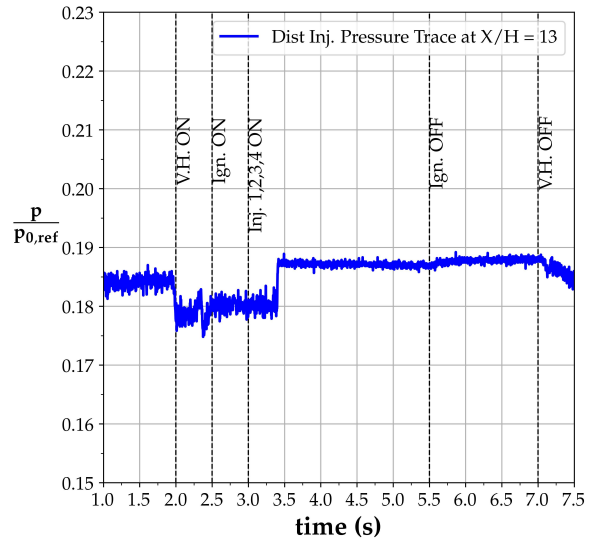


Figure D.52: Pressure evolution for static wall pressure measurement at $x/H = 13$ for distributed injection.

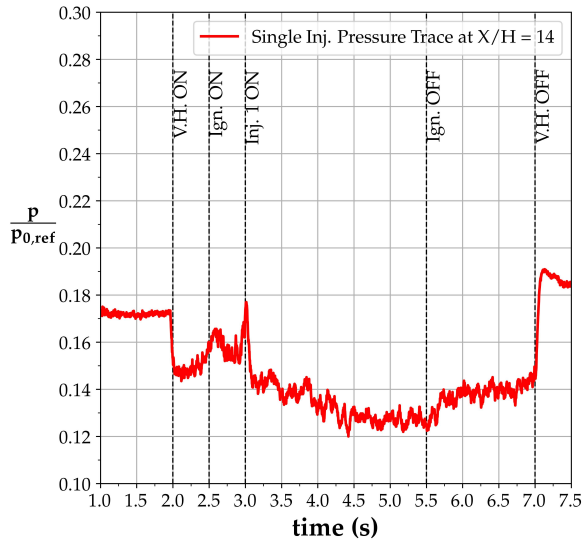


Figure D.53: Pressure evolution for static wall pressure measurement at $x/H = 14$ for single injection

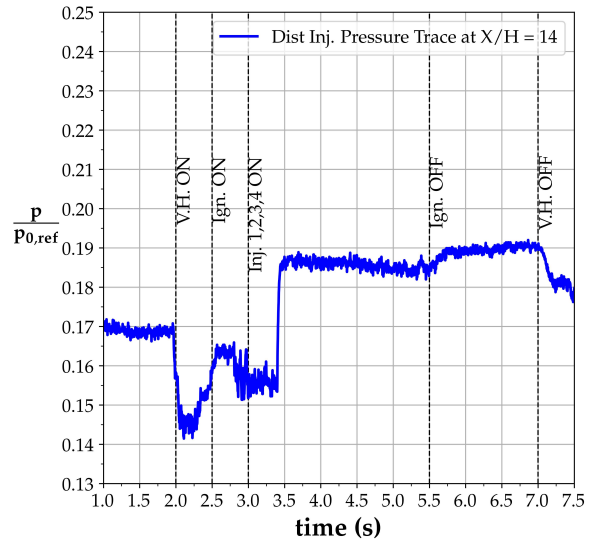


Figure D.54: Pressure evolution for static wall pressure measurement at $x/H = 14$ for distributed injection.

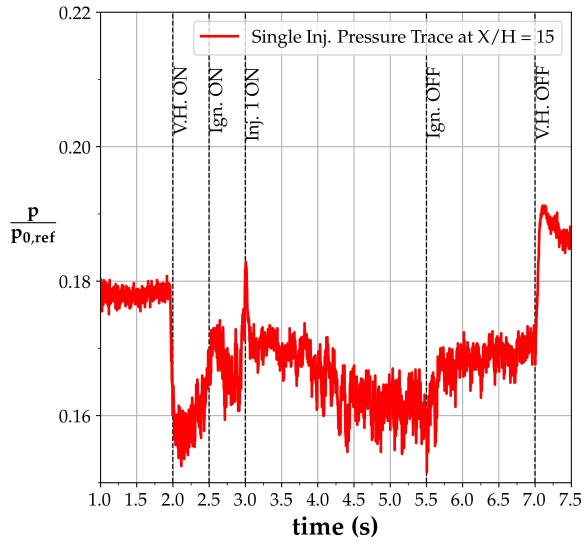


Figure D.55: Pressure evolution for static wall pressure measurement at $x/H = 15$ for single injection

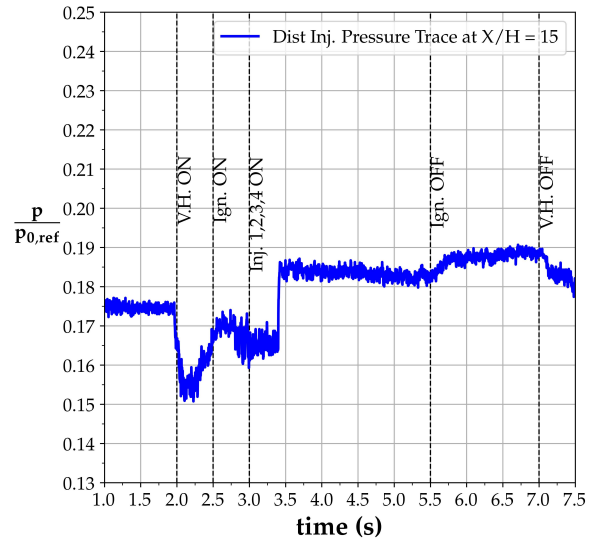


Figure D.56: Pressure evolution for static wall pressure measurement at $x/H = 15$ for distributed injection.

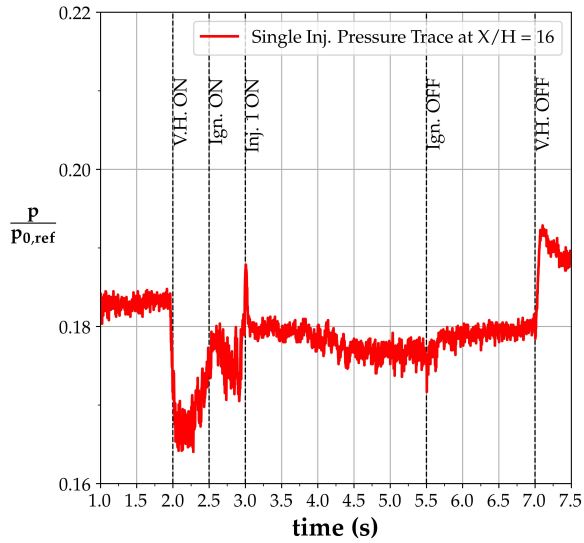


Figure D.57: Pressure evolution for static wall pressure measurement at $x/H = 16$ for single injection

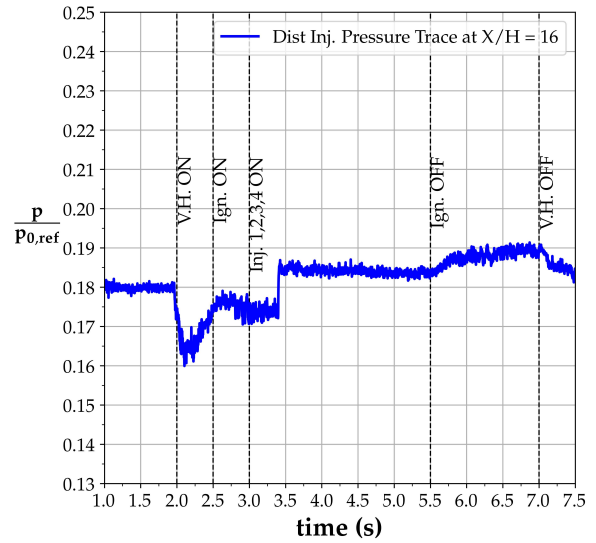


Figure D.58: Pressure evolution for static wall pressure measurement at $x/H = 16$ for distributed injection.

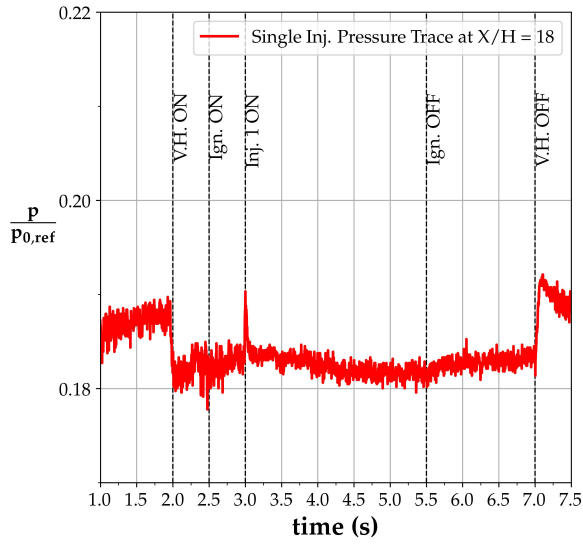


Figure D.59: Pressure evolution for static wall pressure measurement at $x/H = 18$ for single injection

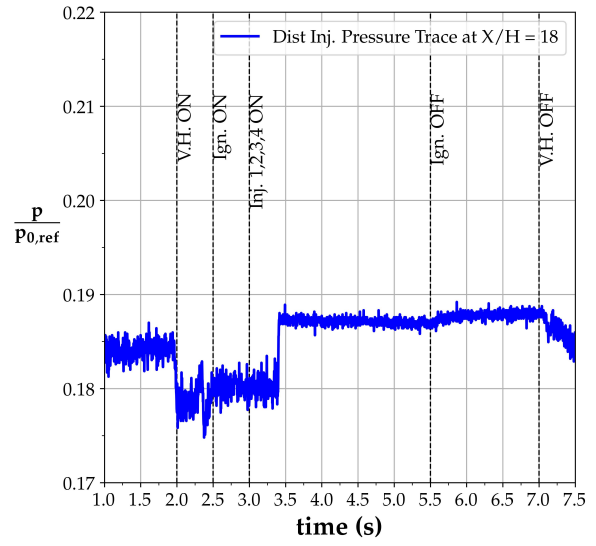


Figure D.60: Pressure evolution for static wall pressure measurement at $x/H = 18$ for distributed injection.

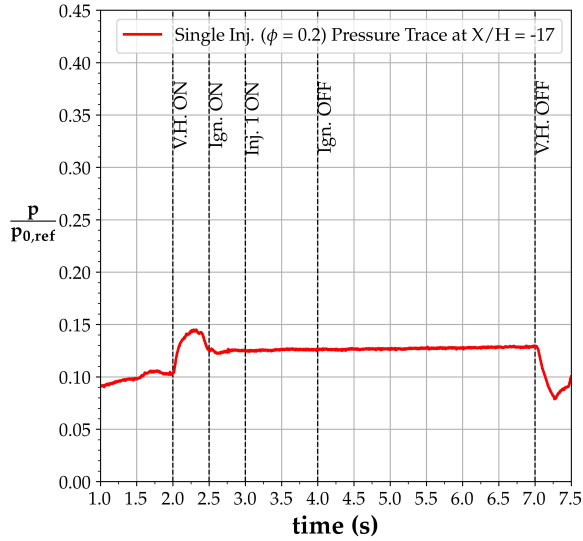


Figure D.61: Pressure evolution for static wall pressure measurement at $x/H = -17$ for single injection (ϕ of 0.20)

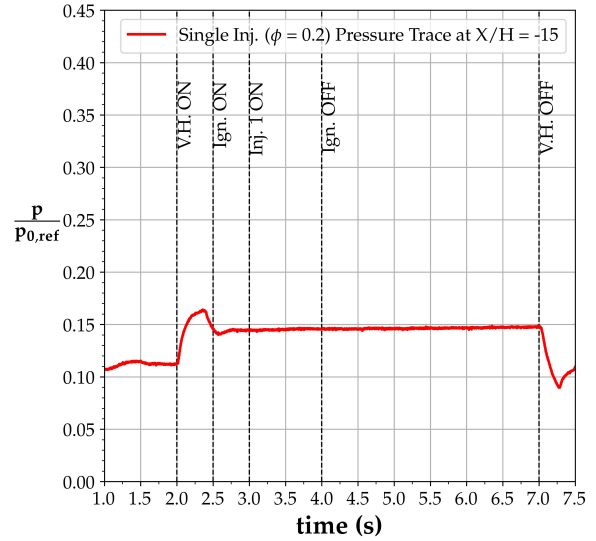


Figure D.62: Pressure evolution for static wall pressure measurement at $x/H = -15$ for single injection (ϕ of 0.20)

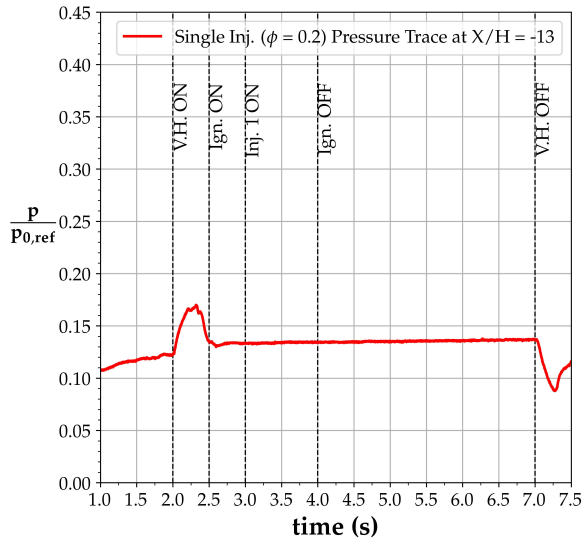


Figure D.63: Pressure evolution for static wall pressure measurement at $x/H = -13$ for single injection (ϕ of 0.20)

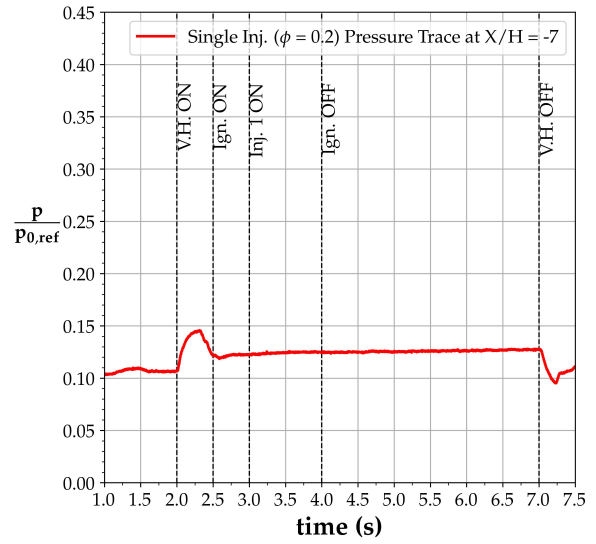


Figure D.64: Pressure evolution for static wall pressure measurement at $x/H = -7$ for single injection (ϕ of 0.20)

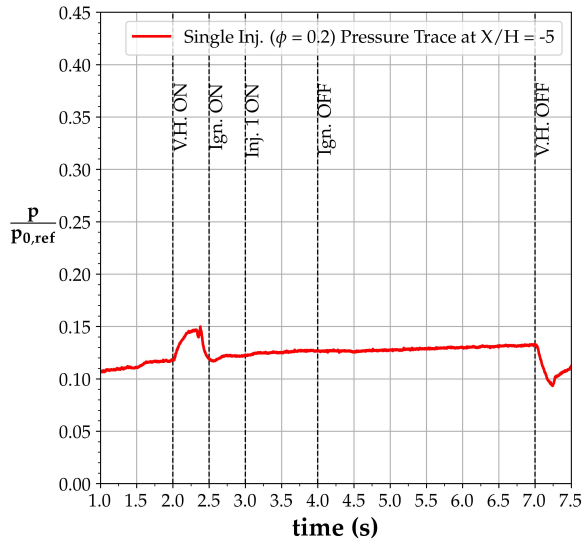


Figure D.65: Pressure evolution for static wall pressure measurement at $x/H = -5$ for single injection (ϕ of 0.20)

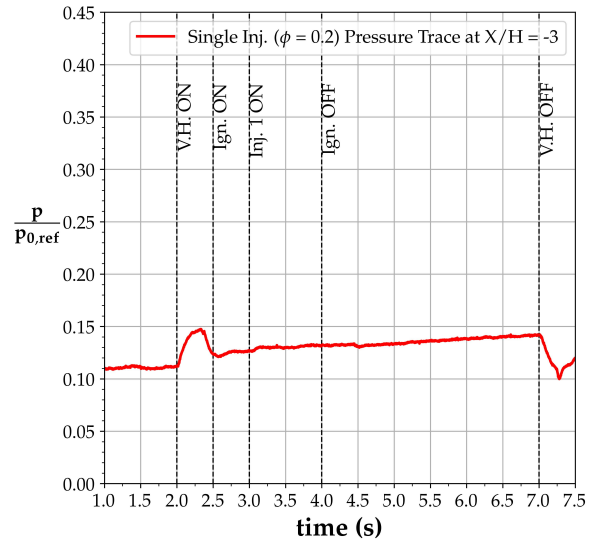


Figure D.66: Pressure evolution for static wall pressure measurement at $x/H = -3$ for single injection (ϕ of 0.20)

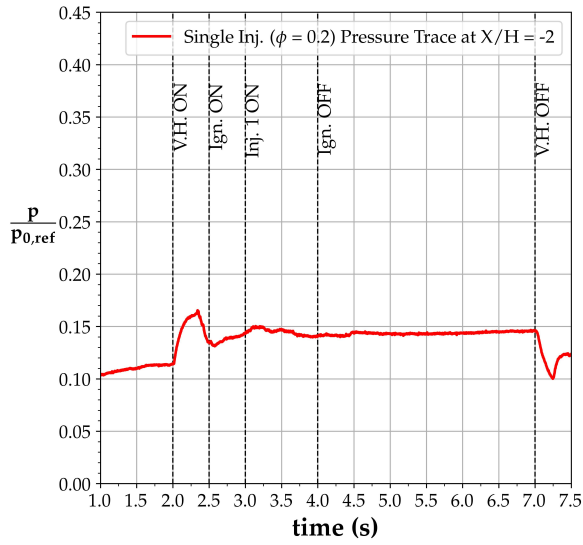


Figure D.67: Pressure evolution for static wall pressure measurement at $x/H = -2$ for single injection (ϕ of 0.20)

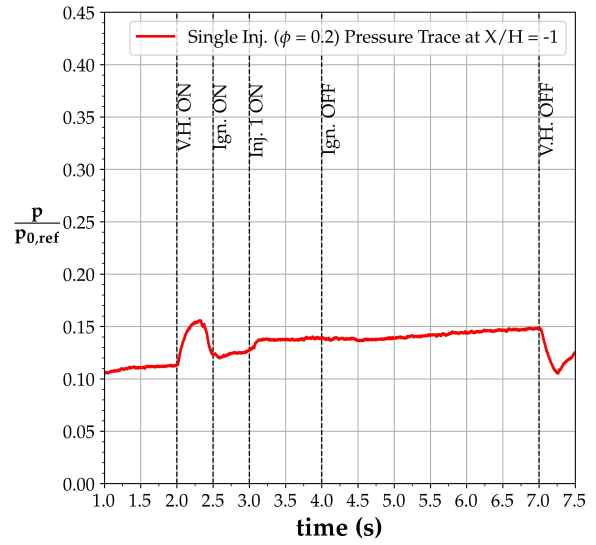


Figure D.68: Pressure evolution for static wall pressure measurement at $x/H = -1$ for single injection (ϕ of 0.20)

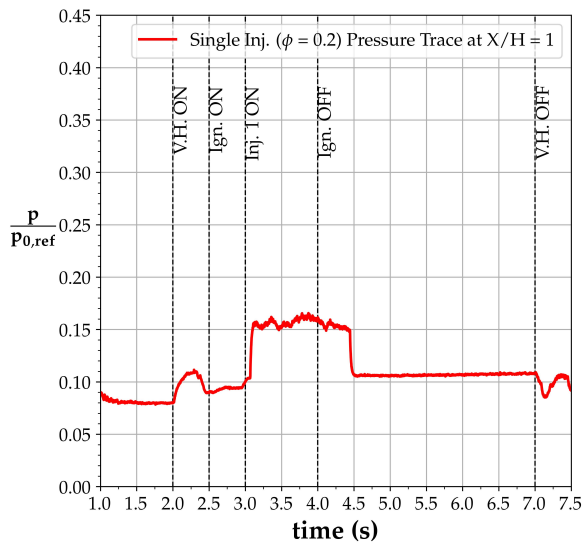


Figure D.69: Pressure evolution for static wall pressure measurement at $x/H = 1$ (bottom port) for single injection (ϕ of 0.20)

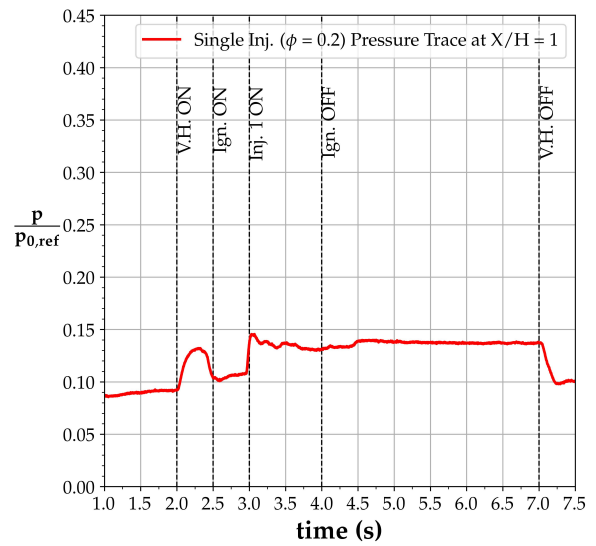


Figure D.70: Pressure evolution for static wall pressure measurement at $x/H = 1$ (top port) for single injection (ϕ of 0.20)

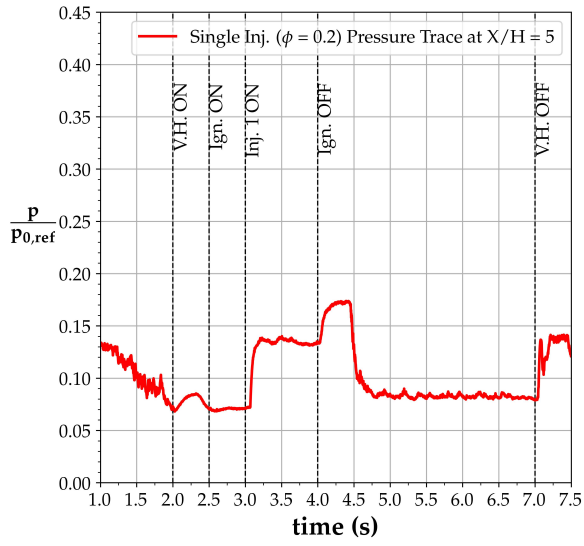


Figure D.71: Pressure evolution for static wall pressure measurement at $x/H = 5$ for single injection (ϕ of 0.20)

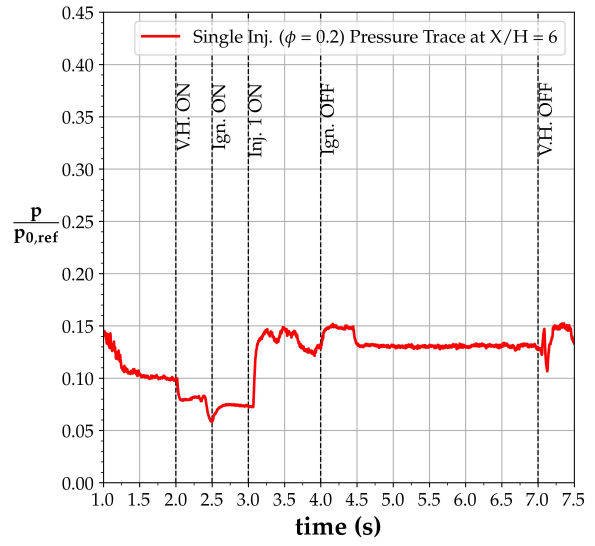


Figure D.72: Pressure evolution for static wall pressure measurement at $x/H = 6$ for single injection (ϕ of 0.20)

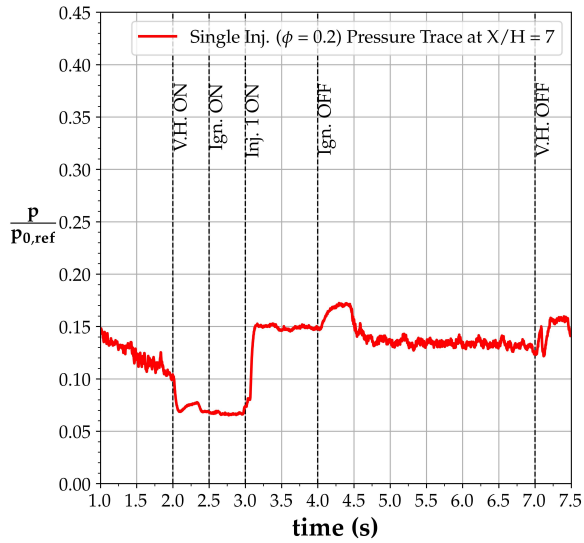


Figure D.73: Pressure evolution for static wall pressure measurement at $x/H = 7$) for single injection (ϕ of 0.20)

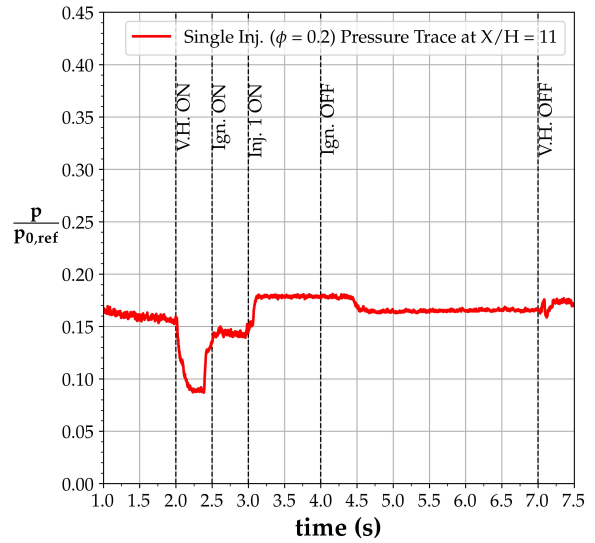


Figure D.74: Pressure evolution for static wall pressure measurement at $x/H = 11$ for single injection (ϕ of 0.20)

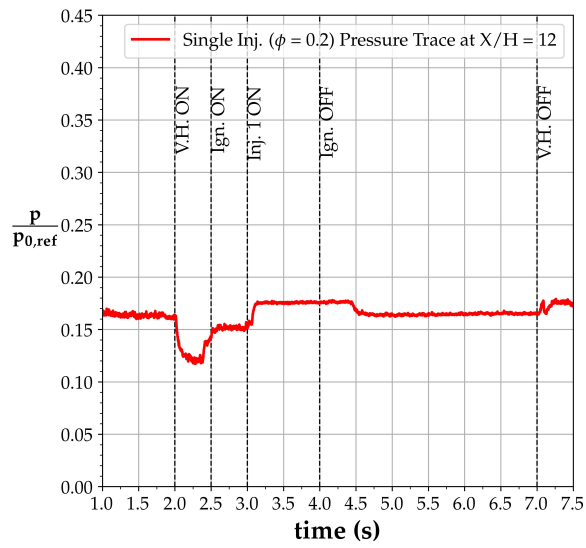


Figure D.75: Pressure evolution for static wall pressure measurement at $x/H = 12$) for single injection (ϕ of 0.20)

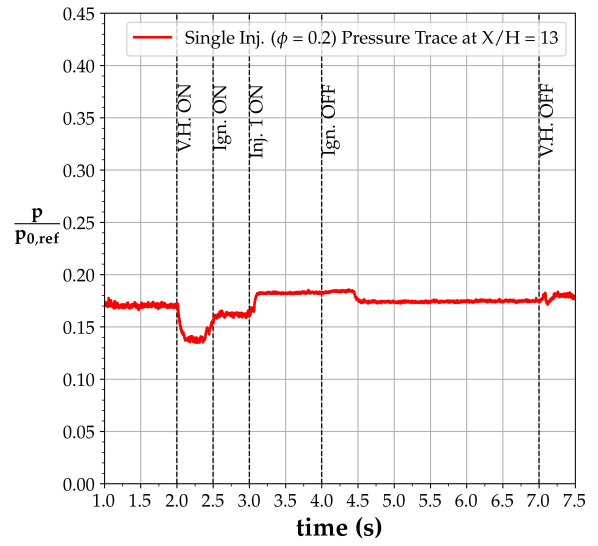


Figure D.76: Pressure evolution for static wall pressure measurement at $x/H = 13$ for single injection (ϕ of 0.20)

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