Experimental Study of Stabilized Oblique Detonation Waves

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1 Introduction

The use of detonations for combustion has been proposed for multiple propulsion and energy generation applications over the past several decades [1]. While the form factor for each application varies, common benefits of detonation combustion over traditionally used deflagration combustion include potentially higher thermodynamic efficiency, shortened combustion chambers through the shorter combustion time scale, and increased mechanical simplicity [1-3]. Of the multitude of possible detonation engine concepts that exist, three broad categories have received the most study, including Pulse Detonation Engines (PDE), Rotating Detonation Engines (RDE), and Standing Detonation Engines (SDE) [3-7]. PDE and RDE prototypes have both been successfully demonstrated in laboratory settings and PDEs have also been field tested in full-scale flight hardware. In recent years, RDEs have received the bulk of research interest for their capability of providing a continuous, quasi-steady operation that may be better paired with turbines or other flight hardware, as compared with PDEs. SDEs have not yet been made into functional prototypes, although there have been several studies into their theoretical effectiveness and the fundamental detonation behaviors that their operation would rely upon. In the realm of SDEs, the Oblique Detonation Wave Engine (ODWE) is one of the more common sub-categories of concepts. ODWEs make use of Oblique Detonation Waves (ODW), as the name states, to create a continuous ignition process in the engine combustion chamber. At high Mach numbers, ODWEs have theoretical performance values greater than Scramjets that use deflagrative combustion [8].

In order for an ODWE to be made practical, a reliable method of detonation initiation and stabilization must be known. Previous work in this field has included testing through means of projectiles fired into fuel-air mixtures, the use of hot jets and geometry in supersonic flows, and through numerical simulations [9-13]. This paper details the experimental study completed using the HyperReact facility that has shown evidence for the initiation and stabilization of an ODW in a continuous flow facility. A ramp was placed in a pre-heated, high-enthalpy, supersonic flow of hydrogen and air to create the needed conditions for the ODW, further detailed below. A quasi-stable reaction was observed wherein the detonation front went through a cycle of being over- and under-driven, but remaining in the region above the ramp. Tests were conducted at multiple pressures, temperatures, and mixture equivalence ratios, which have shown multiple regimes of reaction behaviors within this facility. The stable reaction occurs at the highest pressure and temperature conditions tested in this study.

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2 Experimental Setup

The High-Enthalpy Hypersonic Reacting Facility (HyperReact) experimental facility used for this study is shown in Figure 1. The HyperReact facility is a high-enthalpy, hypersonic reacting facility at the University of Central Florida (UCF). The facility consists of 5 major components, in the order of their location along the axial direction of the facility they are: an in-flow pre-heater, mixing chamber, main fuel injection stage, converging-diverging (CD) nozzle, and an optically accessible test section. The in-flow pre-heater consists of a coaxial hydrogen-air jet flame surrounded by evenly spaced co-flow air jets. The pre-heater is controlled to achieve a stagnation temperature range of 800 - 1,200 K in this study corresponding to a static temperature of 180 – 320 K in the test section. The mixing chamber consists of a square channel with an internal height of 45 mm and a length of 350 mm. This segment of the facility allows for homogenous mixture in-flow feed to the CD nozzle. The main fuel injection introduces the supplementary fuel used for the downstream reactions prior to entering the CD nozzle. The CD nozzle has an axisymmetric square cross section along its entire length. The characteristic length scale for the nozzle is the 45 mm height for both the inlet and exit, and the throat height is 9 mm. The inlet-to-throat and exit-to-throat area ratios are both 25:1. The contracting section of the CD nozzle is designed to produce a uniform velocity profile at the throat and minimize boundary layer growth as detailed by Bell and Mehta [14]. The diverging section of the nozzle consists of a 3D contour derived from an analytical method by Foelsch [15] and a cubic matching function is used [16] to smoothly transition between the 2 segments of the nozzle. Additional details on the nozzle design can be found in [17]. The CD nozzle is designed to provide an exit Mach number of M = 5.0 for dry air [18]. The effective Mach number is dependent on the temperature dependent heat capacity ratio of the mixture entering the nozzle which results in a range of 4.3 to 4.6, depending on the stagnation temperature and

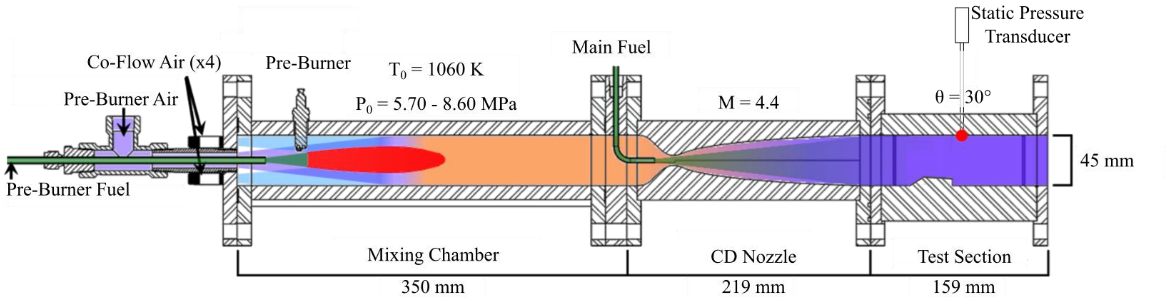

Figure 1: Overview of HyperReact Facility

mixture composition of the test being conducted. The CD nozzle issues the hypersonic flow mixture to the optically accessible test section consisting of a square channel of height 45 mm and length 159 mm. The fuel used for the pre-heater stage and the main fuel injection is 99.99% ultra-high purity hydrogen. Air is provided from a pressure source tank at 34.45 MPa.

Fuel and air mass flow rates supplied to the facility are metered through precision choked orifices. The air orifice is 4.57 mm in diameter. The orifices for the pre-heater fuel and main fuel injection lines vary in size to accommodate the broad range of fueling flow rates needed to cover the extent of conditions tested. Fuel orifice sizes used range from 0.56 mm to 1.57 mm in diameter depending on the mixture fraction. Pressures upstream of each choking orifice are measured using Dwyer 626 absolute pressure transducers with ranges of 0 to 20.68 MPa and accuracy of 1% of the full-scale range. The equivalence ratios of both the pre-burner, φ_{burner}, and the downstream conditions in the test section, φ_{TS}, are calculated based solely upon the amount of O_2 and H_2 in the flow at those locations and the mole fraction of the additional species found is provided in the format (%H_2/%O_2/%N_2/%H_2O). The stratification of the fuel results in a test section fuel profile that is shown in Figure 2, which was experimentally determined through Raman imaging of the facility during non-reacting operation by correlating laser-scatter to local H_2 concentration, detailed in [19]. The local premixed mixture equivalence ratio (φ_{TSL}) near the ramp surface is then used in calculating φ_{TSL_AVG}. φ_{TSL_AVG} is defined as being the average fuel concentration between the test section wall at y/h = 0 and the selected upper boundary. ODW characteristics, including M_{CJ} and ODW stability limits were calculated using the φ_{TSL_AVG} values determined by this method.

A 30 degree turning angle ramp is used for stabilizing the detonation wave. The ramp spanned the full width of test section and is placed at 44 mm downstream of the CD exit plane. The height of the ramp is fixed at 7.5 mm to avoid a blockage ratio higher than 17% within the test section. The aft face of the ramp is relieved at a 3 degrees angle relative to the test section wall. This allows the flow to partially re-expand along its length. Test Section static pressure measurements are taken at the test section top wall mid-plane, marked with the red dot in Fig. 8.

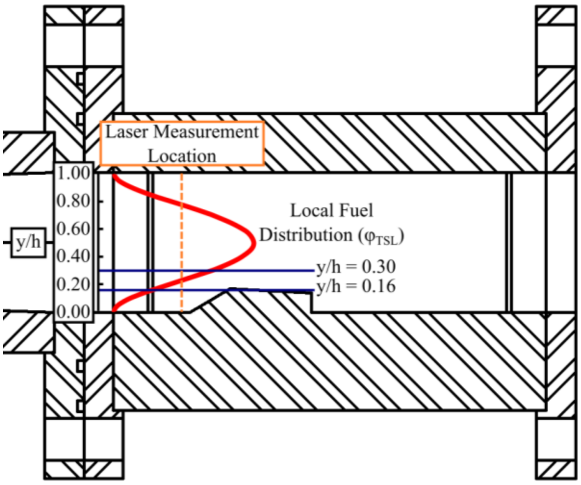

Figure 2: Schematic of fuel measurement location and curve-fitted local fuel concentration. Limits used to determine φ_{TSL_AVG} also shown.

The ODW is recorded using simultaneous high-speed shadowgraph and visible range wavelength 450-875nm chemiluminescence imaging. The test section has fused quartz windows on the side walls for full optical access to an interrogation region of 105 mm long and 45 mm high. The schlieren system consists of a Z-type setup using two 152.4 mm spherical mirrors, with focal lengths of 1.52 m, and a high-power Luminus PT-121-G LED light source. Both the schlieren and chemiluminescence images are captured using Photron SA1.1 high-speed cameras recording at 30 kilo-frames-per-second (kfps). The schlieren camera is equipped with a Nikon 70-300 mm f/4-5.8 lens and images with a 640 x 288-pixel resolution resulting in a spatial resolution of approximately 164 μm/pixel. The chemiluminescence camera, equipped with a Nikon Nikor 50mm f/1.2 lens, was operated with a resolution of 350 x 163 pixels, resulting in an approximate spatial resolution of 300 μm/pixel.

3 Results and Discussion

Overlaid shadowgraph and chemiluminescence images of a stabilized detonation on a ramp in a hypersonic flow are shown in Figure 3. Figure 3(A) shows the baseline non-reacting hypersonic flow in which the main fuel injection was not activated. Figure 3(B-D) shows the same hypersonic flow with the fuel turned on, which resulted in the generation of a stabilized oblique detonation wave (ODW). The turning angle of the ramp is $\theta = 30°$. The flow stagnation pressure (P_0) is 5.63 MPa and the stagnation temperature (T_0) is 1060 K resulting in an effective exit Mach number of 4.4. The fueled case shown here has a mixture molar composition of major species $H_2/O_2/N_2/H_2O$=13.2/9.3/62.0/14.7%(yielding a global H_2/O_2 equivalence ratio of $\varphi_{TS} = 0.71$).

Prior to fueling the facility, the non-reacting flow field was analyzed to confirm the oblique shock wave produced by the ramp matched the theoretical adiabatic oblique shock solution for a 30° ramp as a means of confirming the flow Mach number. For the given nozzle area ratio (A/A*=25), the non-reacting hypersonic flow shows the predicted oblique shock angle (β) of 42° for an inflow Mach number of 4.4 with a ratio of specific heats (γ) of 1.3. Once fuel is introduced, an oblique detonation wave is initiated over the ramp and can be sustained for the duration of the run, ranging from approximately 0.5 seconds to 2.5 seconds. During the reaction, the highest chemiluminescence signal intensity is observed immediately above the ramp due to the presence of the detonation wave at that location. The sustained detonation is driven by the reacting shock (RS1-3) in Figure 3. As the incoming flow passes through the leading shock (S1-3), it enters the induction region. In the induction region, the mixture is heated by the temperature rise across the shock. This heating allows for the reaction process to occur and the formation of a steeper angled reacting shock coupled with the reaction that makes up the detonation wave [20]. The static pressure profile shown in Figure 4, measured downstream of the ramp, shows a clear pressure rise generated by the reaction when compared to the baseline non-reacting flow. The peak pressure reaches 2.7 times the baseline non-reacting pressure.

The detonation front remained above the surface of the ramp for the duration of the reaction. While the detonation is sustained, the location of the detonation front fluctuates throughout the run in a cyclical fashion. The shock structure ahead dynamically responds to the fluctuations in the detonation front as seen in the shadowgraph image time series in Figure 3. The leading reaction front remained at the inflection point between shocks S and RS, while the reactions along the ramp surface cyclically travel upstream and downstream. It is believed that the reaction goes through a cycle-to-cycle variation of underdriven-to-overdriven detonation due to the turbulent nature of the reacting detonation flow. Additional burning takes place behind the detonative reaction front, above the leading reaction front, and further reactions occur upon reaching to the top wall, behind the reflected shock.

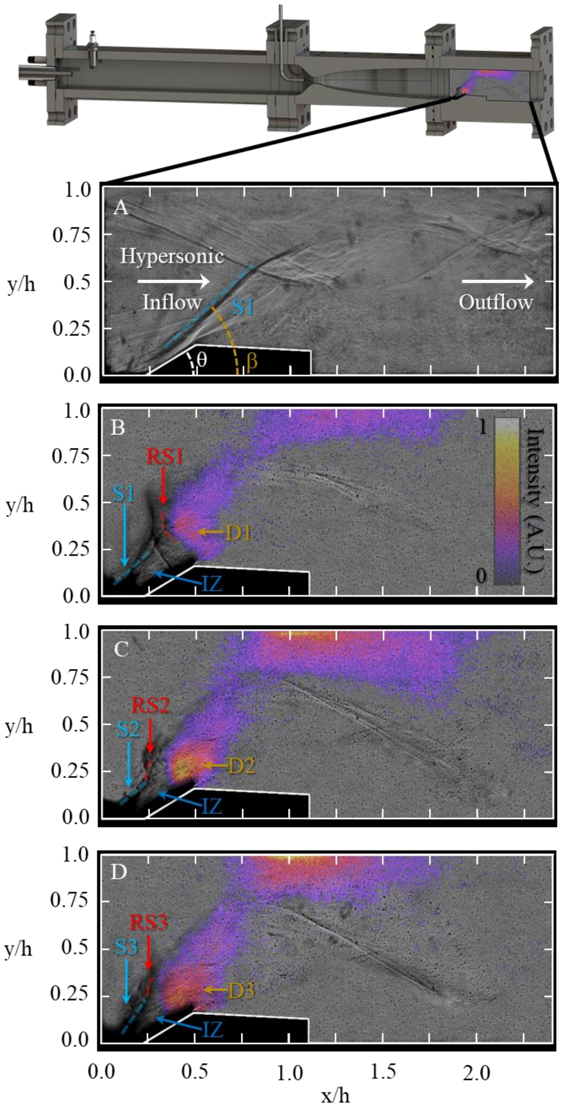

Figure 3: Shadowgraph images overlaid with chemiluminescence signal for (A) non-reacting case and (B-D) multiple times during reacting case.

An important aspect for the detonation wave stability is achieving the ideal balance in mixture composition and heat release for reaction with the high-Mach number flow. A high heat release will result in a detonation that is overdriven and propagates upstream opposing to the flow. On the contrary, a low heat release will result in the reaction receding downstream and deflagrating. Pratt proposed a model to predict the limits at which ODW stability can be achieved [21]. The model generates a theoretical estimate of the range of turning angles and flow Mach numbers over which oblique detonation wave stability is possible for a given mixture composition, static temperature, and amount of heat release produced by the detonation. The stability band is defined as the conditions that exist on the shock polar, shown in Figure 5, between θ_{CJ} and θ_{Max}. At a given flow Mach number, θ_{CJ} is the minimum turning angle for which the detonation calculated can be stabilized, and θ_{Max} is the max turning angle at which the ODW will remain attached to the ramp. The shock polar originates from the Chapman Jouguet (CJ) Mach number, M_{CJ}, which is the Mach number at which a detonation would freely propagate in a quiescent mixture of the same composition and static temperature. Flow Mach numbers below that value have no stable solution. Figure 5 shows the stability band for an imperfectly mixed flow, where the fuel concentration is greater in the core of the flow as compared to the edges. This stratification of the fuel means that the detonation characteristics vary through the flow as well, which results in a local equivalence ratio (φ_{TSL}) of approximately 0.30 and $M_{CJ} \approx 3.21$ near the ramp surface where the detonation occurs. This suggests that the test condition (M = 4.4, θ = 30°) lies close to the theoretical stability limit. When the detonation characteristics are calculated using the assumption of a perfectly mixed flow, this gives a global test section equivalence ratio (φ_{TS}) of 0.71 and M_{CJ} = 4.37. This makes the test case lie within the detached ODW region, close to the minimum freestream Mach number at which an ODW can exist.

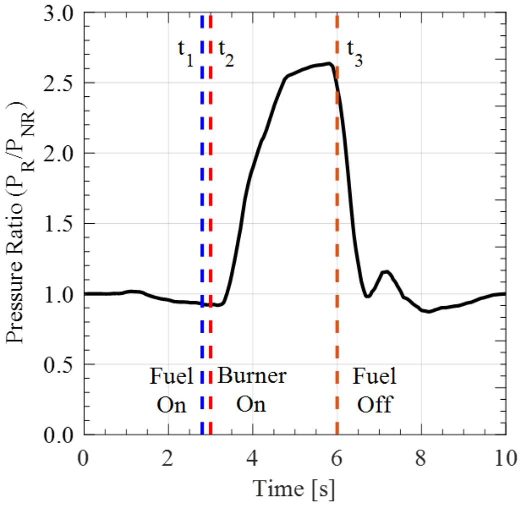

Figure 4: Average Test Section Reacting vs. Baseline Pressure Ratios

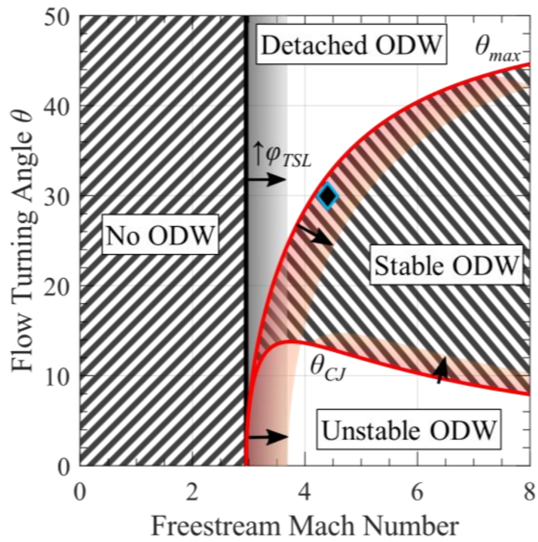

Figure 5: ODW stability band range for case shown in Figure 3.

4 Conclusion

The HyperReact facility has successfully demonstrated its potential for creating a stable ODW reaction. At sufficiently high pressures, Mach numbers, and temperatures, a stable reaction can be consistently created within the facility. Optical diagnostics of the system show expected shock structures and, combined with the chemiluminescence imaging and pressure measurements, are evidence of the reaction being a detonation. Future work will include increasing the temperatures and pressures further with the goal of further increasing the stability of the system and making the system operable at higher Mach numbers and with different ramp angles.

Acknowledgements

This work is sponsored by the Air Force Office of Scientific Research (FA9550-16-1-0403, 19RT0258/FA9550-19-0322, Program Manager: Dr. Chiping Li)

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