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Preliminary Results from Narrow Channel Facility Experiments at Purdue University

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OH* chemiluminescence and pressure measurements were acquired during the recommissioning of the Caltech Narrow Channel Facility (NCF) at Purdue. A high degree of versatility was built into the newly designed NCF reactant delivery system to allow for efficient testing of multiple reactant combinations. The ability of the dynamic injection, C_2H_2-O_2 driven branched initiator to produce a planar wave capable of detonating less sensitive mixtures was verified. The detonation wave speed of multiple hydrogen-oxygen-argon and hydrogen-oxygen-nitrogen mixtures, spanning two instability regimes, was studied and agreement with the Chapman-Jouguet velocity was found for each. Ultrahigh-speed chemiluminescence imaging captured 8-10 frames of the detonation wave traveling through the optically-accessible section. These measurements revealed that the structure of the reaction zone increases in complexity as the mixture transitioned from the weakly unstable to moderately unstable regime.

I. Introduction

A detonation is a shock-coupled, supersonic combustion wave in which the rate of thermo-chemical energy conversion is so much greater than the concomitant rate of gas expansion that the heat release is considered to occur within a constant volume.[1,2] Under such conditions, the enthalpy change due to combustion causes an increase in both temperature and pressure locally, within the combustion wave, as well as globally, following the wave passage. For many years, engineers have attempted to harness the power of detonations for practical purposes. RDEs, the most promising apparatus for achieving this goal, operate continuously, with one or more detonation waves that circumscribe an annular combustion chamber. RDEs require only one ignition - DDT process, at initiation, and the reactants are continuously supplied to the combustion process through a conventional, (quasi-) steady reactant injection system.[3–7] However, the mechanisms of detonation wave propagation in RDEs are very poorly-understood and, at present, these systems are not able to demonstrate the cycle efficiency gains that are predicted to be possible. Many open questions remain, and a fundamental research effort will be required to characterize the highly-nonlinear, intrinsic structure and dynamics of detonation waves subject to the non-classical conditions present in an RDE.

The structure of an unsteady detonation front was first observed by White[8] and has since been the focus of numerous other studies.[9–14] A schematic representation of the cellular detonation structure is depicted in Figure 1a. The leading shock is not planar or steady, but rather exhibits spatially and temporally varying oscillations due to triple-point intersections with transverse waves within the reaction zone. Transverse wave motion is oriented perpendicular to the global direction of detonation wave propagation. Near the locus of collision (the triple point), a highly localized region of high enthalpy gas is generated due to heat release, which drives the incident shock forward. Following triple point passage, the gases behind the mach stem expand and the local wave speed decays until the passage of another triple point. This unsteady process occurs with a characteristic time-scale associated with the triple point intersections across the detonation front. The corresponding length scale is the detonation cell-size. The triple-point trajectories and intersection

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length scales along the channel wall can be measured using the soot foil technique; an example is shown in Figure 1b. The stability of a given detonation can be qualitatively characterized based on the regularity and size of the cellular detonation structure.

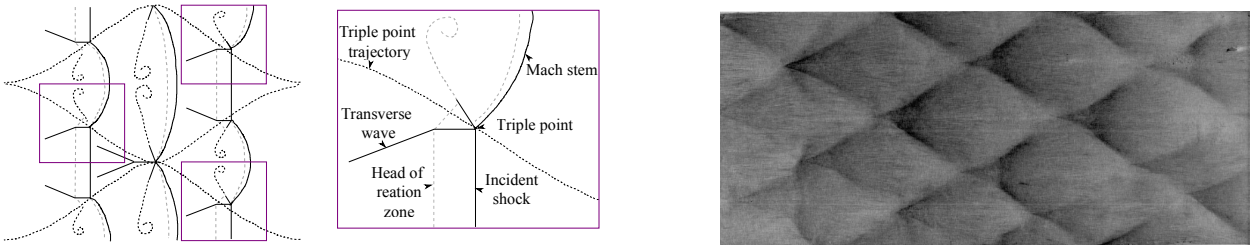

Figure 1: The (a) idealized two-dimensional structure of a detonation wave and (b) soot foil from a $2H_2 - O_2 - 17Ar$ detonation in the NCF at Caltech.[14]

The flow and boundary conditions present in RDEs are a significant departure from the canonical conditions studied above and can strongly affect the transverse wave structures that support detonation propagation. One factor is the curvature of the annular combustion chamber. Transverse waves, oriented radially within the chamber, are focused upon reflection from the concave surface of the cylindrical outer wall and diffracted by the convex inner wall, leading to radial variation in triple point strength across the detonation front. Another factor is the presence of strong gradients in reactant properties, including flow composition. After passage of the detonation wave, reactants must be reintroduced to the combustion chamber before the next wave arrives at the injection site. This processes typically occurs with a time scale of $\mathcal{O}(10^{-4})s$. The operation of these devices, therefore, requires high-speed, compressible injection flows that can produce large variation in flow composition due to unsteady (non-premixed) injection and product gas entrainment. When a detonation encounters these composition gradients, a complex interaction evolves that is coupled to the local manifestation, relative strength, and orientation of the detonation.

In this work, we describe the development of an experimental capability to perform time-resolved measurements of the reaction zone structure and dynamics in a propagating detonation. The experimental platform for this demonstration is the GALCIT *Narrow Channel Facility* (NCF), which can provide suitably canonical conditions for validation of the techniques.[14] The NCF was relocated to Purdue to enable the application of ultrahigh-speed optical diagnostics with sufficient spatial and temporal resolution and dynamic range to achieve the measurement objective. The ultimate goal is to apply these tools to examine, in detail, issues relevant to RDEs such as detonation propagation in stratified flows with continuous concentration variations. The NCF and associated diagnostics will be used to characterize these processes with high-quality experimental data, supporting scientific insight at the reaction zone level.

II. Experiment Configuration

II.A. Narrow Channel Facility

For the following canonical study, a suitable level of fidelity can only be achieved with a single-shot experiment; one that is specifically designed to provide a physical-traceability record of the evolution of each combustion wave. The *Narrow Channel Facility* (NCF) was developed by researchers in the Explosion Dynamics Laboratory at Caltech to study the unstable structure in gaseous detonations.[14] It was utilized at Caltech to generate key contributions to current understanding of reaction zone structure, as a function of mixture conditions.[14,15] The NCF is a high aspect ratio, rectangular channel with a height of 152 mm and width of 18 mm. The dimensions were chosen such that the width is nominally smaller than the detonation cell size for a targeted range of mixtures and test conditions. This configuration effectively suppresses transverse wave motion across the width of the channel, generating a two-dimensional detonation structure across the channel height that is conducive to the application of planar (and path-integrated) optical diagnostics. NCF experiments have been performed with a range of reactant mixtures including hydrogen, ethylene, and propane fuels with oxygen and various degrees of nitrogen and argon dilution.

The NCF spans a length of 4.2 m and has 177 mm diameter optical windows near the aft end of the channel for visualization of the full-developed detonation. The reactants are loaded into the channel using the method of partial pressures. The chamber is initially purged with the diluent gas (typically Ar or N_2)

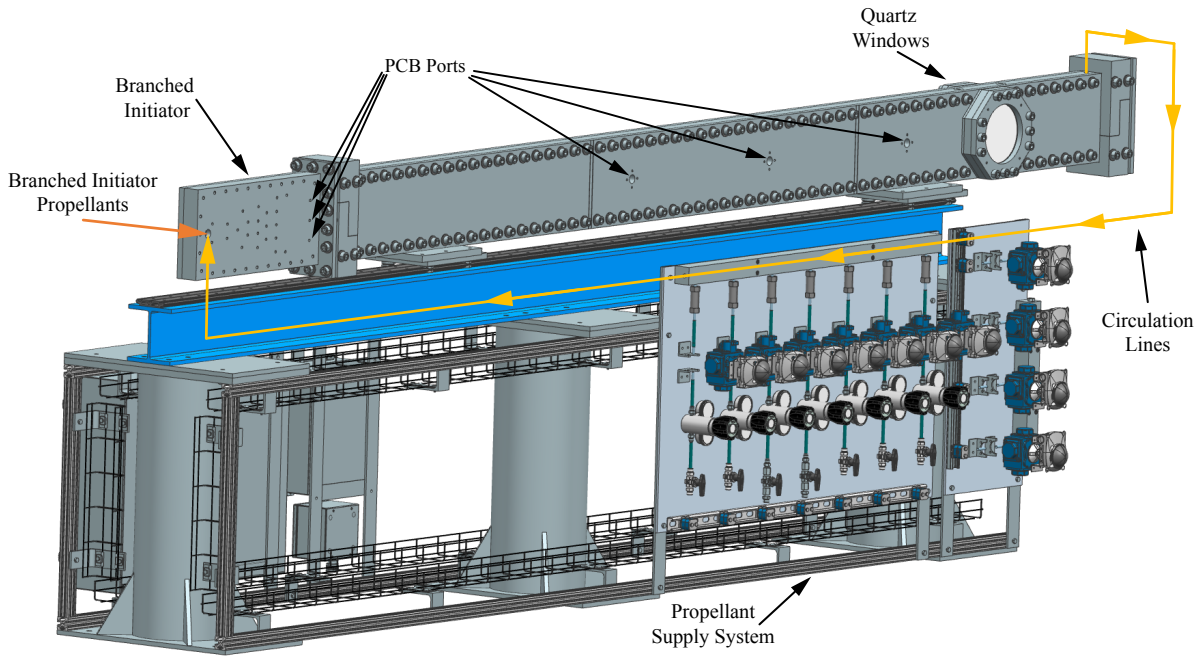

Figure 2: CAD rendering of the GALCIT *Narrow Channel Facility* installation at Purdue.

used in the test, then drawn to a pressure of 3.5 kPa using a vacuum pump. With known mass of the chamber contents, the fill process begins with introduction of the diluent gas into the chamber until the partial pressure corresponds with the prescribed mole fraction for the test. The fuel and oxidizer are then loaded by the same procedure, with a short delay between each step. The mixture is circulated throughout the loading process to homogenize the reactants. Once the reactants are loaded to the target initial pressure and mixture conditions, they are circulated for an additional thirty seconds prior to initiation. The planar detonation is driven by a branched initiator, designed by Jackson and Shepherd.[16] The initiator operates with an equimolar C_2H_2-O_2 mixture and is ignited with a spark plug. Following a rapid deflagration-to-detonation transition (DDT), the initial detonation is split into a symmetric network of channels that divide it into sixteen wave-fronts, distributed across the height of the channel. The waves quickly merge to produce a planar detonation within the channel that propagates into the test gas. Once the test is complete, the system is vented of all product gases and purged with an inert gas.

II.A.1. Propellant Supply System

Although the architecture of the NCF has not been altered since it was developed at Caltech, the propellant delivery system has been redesigned to integrate with the infrastructure at Purdue. Reactant circuits have been configured to allow for versatile and robust control of the propellant loading process from up to seven independent sources: three fuels, two oxidizers, and two inert gases. Specific consideration was given to the need for accurate and repeatable loading of small quantities of gas, approximately 3 grams per test. All circuits are isolated from the NCF with a computer-controlled pneumatic valve. An orifice is installed immediately downstream of each valve to restrict the flow rate. The supply pressures are regulated to further ensure that the fill rate is sufficiently low for robust control with the resolution of the pneumatic valve actuation time. The reactant loading process is controlled with an autosequence and takes approximately 40 seconds, depending on the test condition. All cases presented in this work were repeated to within 5% variance of the partial pressure of each reactant.

II.A.2. Branch Initiator

The branched initiator is a critical component of the system, enabling repeatable, direct initiation of the test gas mixture. All reactants enter through the same gas inlet, shown in Figure 3a. Injection of the C_2H_2-O_2 displaces the test gas mixture in the initiator channels and raises the pressure of the NCF to the desired initial detonation pressure. Following initiation, propagation of the detonation through the branched

initiator after the spark plug fires was captured by Jackson and Shepherd and is shown in Figure 3b. Further specifications about the design and dimensions of the branch initiator are reported in Jackson and Shepherd, 2006.[16]

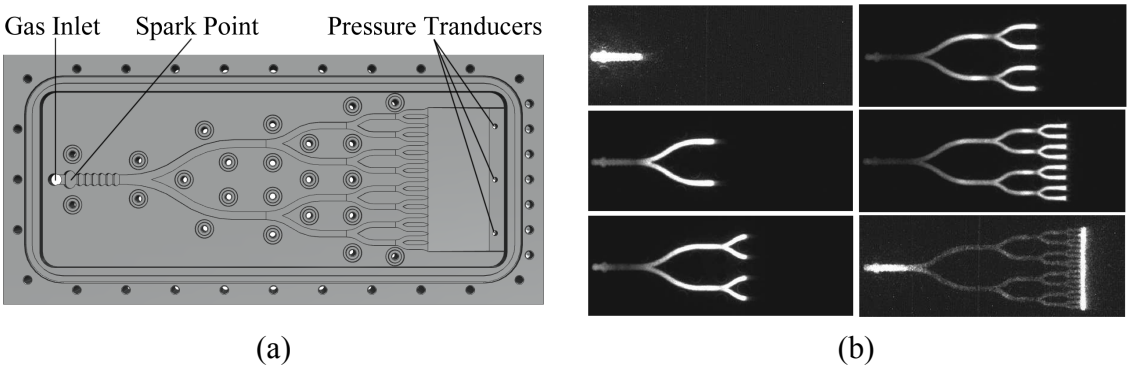

Figure 3: The branched initiator (a) CAD rendering and (b) chemiluminescence images of wave travel.[16]

Dynamic injection and tuning of the acetylene and oxygen mixture is accomplished with an independent control scheme. Both the acetylene and oxygen circuits include a manual regulator whose pressure is set such that when the circuits' pneumatic valves are opened concurrently the appropriate mass of each gas will travel through orifices to produce an equimolar mixture. To fill the branched initiator, both the acetylene and oxygen valves are opened until the mixing chamber reaches the desired pressure, as monitored by a pressure transducer. Once that pressure is met, the initiator isolation valve opens for 1 second to allow the mixture to fill the branched initiator channels. Immediately after closure of the initiator isolation valve and verification that all other valves on the rig are closed, the spark plug fires.

II.B. Measurement Systems

Loading of the propellants for both the detonation channel and the branched initiator is monitored by a GE Druck UNIK 5000 pressure transducer. Each pressure transducer is accurate to within $\pm 0.055\ kPa$. A K-type thermocouple is placed just upstream of the branched initiator entrance and is used record the pre-detonation temperature. The sampling rate for all three instruments is 1 kHz and is recorded with a National Instruments DAQ. Both the pressure transducers and thermocouple are isolated from the channel prior to detonation with ball valves.

Once the spark plug fires, pressure fluctuations throughout the NCF are recorded using seven PCB 113B26 high frequency pressure transducers sampling at a rate of 2 MHz. Three HF pressure transducers, called out in Figure 3a, monitor the planarity of the wave as it enters the test section. The remaining four HF pressure transducers are used to track the progression of the detonation wave as it traverses the channel. Figure 2 identifies the location of three HF pressure transducer ports in the channel, which are 635 mm apart. The most upstream HF pressure transducer is located 1.47 m from the exit of the branched initiator. The most downstream HF pressure transducer is placed in the base of the channel just upstream of the window center-line, 3.1 m from the exit of the branched initiator.

In this work, chemiluminescence imaging of OH* will be performed to acquire spatial information about the reaction field. Chemiluminesance emission is captured through a UV filter, centered at 320 nm with 40 nm bandwidth (Semrock 320/40 Brightline Bandpass), in order to sequester the hydroxl radical signal from other flame emissions. The filtered signal is collected through a 98 mm focal length, f/2.8 objective lens (Cerco Sodern Type 2178) before being amplified with a Lambert HiCATT 25 intensifier with 1:1 relay lens. The signal is recorded with a Phantom V2512. The camera recording rate is set to 99 kHz in order to capture the largest field of view possible and still maintain a small enough temporal resolution to resolve multiple instances of the wave passage.

III. Results

Presented in Table 1, the conditions studied this work were chosen to closely follow (and repeat) tests from the GALCIT database for the purposes of verification and validation.[17] One fuel and oxidizer combination, H_2 and O_2, was studied with two diluents, Ar and N_2. The initial pressure and temperature was held

constant, at 20.7 kPa and 304 K respectively. The mixtures in the table are classified based on instability level, which has been referenced from Austin, 2003.[14]

Table 1: Detonation velocity and stability levels for test gas mixtures studied in this work.

Mixture	U_{CJ} $[m/s]$	Instability
$2H_2$-O_2-7Ar	1648	Weak
$2H_2$-O_2-9Ar	1589	Weak
$2H_2$-O_2-3.5N_2	1957	Moderate
$2H_2$-O_2-4.6N_2	1866	Moderate
$2H_2$-O_2-5.7N_2	1790	Moderate

III.A. Branched Initiator Operation

Operation of the branched initiator was consistent, regardless of the test gas mixture. Figure 4 depicts a typical pressure time-history measured by the three high frequency pressure transducers axially co-located at the exit plane of the branched initiator. The initial pressure is scaled to match the pressure in the channel just before detonation; in this work, 20.7 kPa. A coincident increase in pressure across all three transducers indicates that the individual detonations exiting the channel array have successfully coalesced into a planar front. In contrast, a time-offset of these pressure peaks would be indicative of a non-planar, or otherwise distorted driver wave emanating into the test gas. All tests presented in this work have driver wave arrival within a 2 μs total time separation.

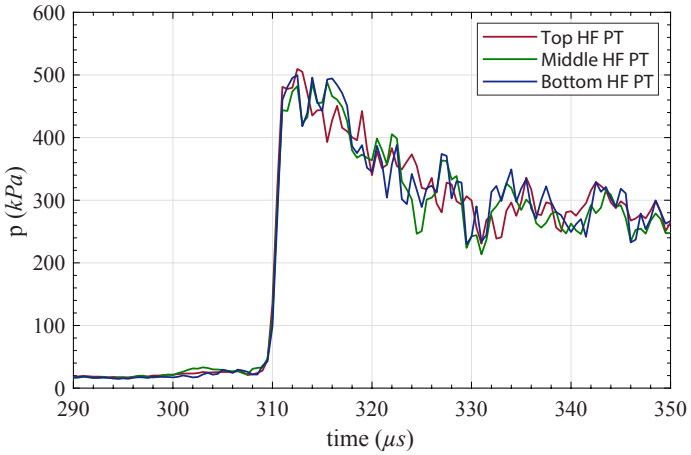

Figure 4: Pressure-time history of the exit plane of the branched initiator.

III.B. Detonation Wave Velocity

Once the driver wave transfers to the test gas mixture, a self-sustained planar detonation wave is generated in the channel. The evolution of this process can be characterized by the wave propagation speed within the channel. This quantity is computed from the pressure-time history measured by the high frequency pressure transducer array distributed along the channel (Figure 2). A representative pressure trace of the detonation traveling through the channel is shown in Figure 5. Each pressure transducer registers the wave passage as an impulse response, producing a near vertical line. The time at which each pressure transducer shows this transition is recorded and a divided by the known distance between measurement locations to calculate wave velocity. The measured velocity at each point is compared to theoretical Chapman-Jouget Velocity (U_{CJ}) using the velocity deficit ∂U, where $\partial U = (U - U_{CJ})/U_{CJ}$. The partial pressure of each reactant, initial mixture temperature, and initial mixture pressure are used as inputs to the NASA Chemical Equilibrium with Applications (CEA) program to compute U_{CJ} for each test. Each case, presented in Table 1, was repeated twice and the corresponding velocity deficits are shown in Figure 6.

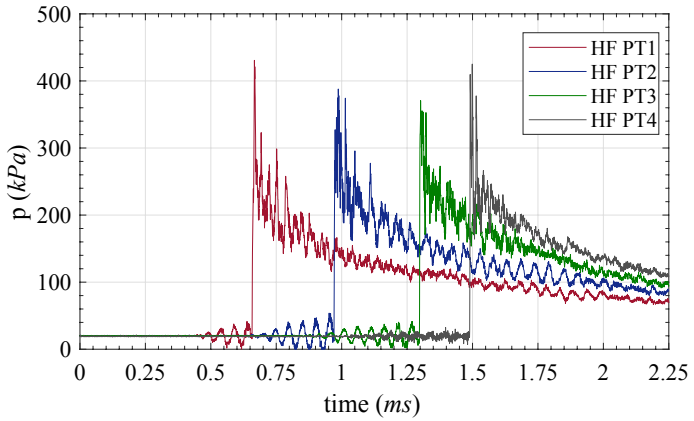

Figure 5: Pressure-time history of a detonation wave in $2H_2$-O_2-$3.5N_2$. The high frequency pressure transducers are located at the following downstream location from the branched initiator exit; HF PT1: 1.47 m, HF PT2 = 2.11 m, HF PT3: 2.74 m, HF PT4: 3.10 m. The detonation exits the branched initiator at time = 0 ms.

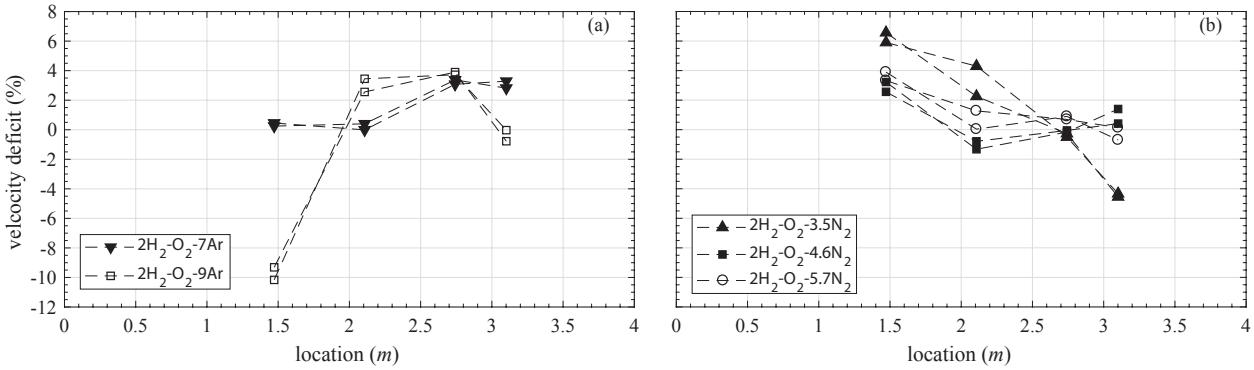

Figure 6: Velocity deficit for (a) argon diluted mixtures and (b) nitrogen diluted mixtures.

Mixtures diluted with argon are presented in Figure 6a and those with nitrogen in Figure 6b. All cases show good repeatability, with a maximum variance of 2%. The two argon mixtures tested show starkly different behavior. With less Ar dilution ($2H_2$-O_2-7Ar), the wave velocity remains steady, just above U_{CJ}, for the first two measurement locations and then increases to about 3% above U_{CJ}. The case with more argon dilution ($2H_2$-O_2-9Ar) shows a velocity deficit of -10% upstream in the channel before eventually reaching U_{CJ} at the window location. One explanation is that the detonation has not yet fully developed at the location of the first pressure transducer, which would be expected for a more dilute mixture. Nitrogen diluted mixtures display much more consistent behavior with the varying levels of dilution tested. All mixtures start at approximately 2% - 6% above U_{CJ} before decreasing toward U_{CJ} at the window location. The least dilute mixture, $2H_2$-O_2-$3.5N_2$, continues to decrease below U_{CJ}, indicating that the wave is not sufficiently sustained. However, the other two conditions, $2H_2$-O_2-$4.6N_2$ and $2H_2$-O_2-$5.7N_2$, reach U_{CJ} and remain steady as the wave travels into the optical section.

III.C. Chemiluminescence Imaging

High-speed chemiluminescence imaging provides insight into the reaction zone, corresponding wave structure, and dynamics that are not otherwise observable with probe-type instrumentation. Figure 7 presents a single frame from each mixture tested as the wave passes through the midpoint of the window. It is evident in all cases that the global wave structure is nearly planar and vertical, which is an indication of the proper function of the branched initiator. Figure 7b shows a slight forward inclination of the wave, with about 2 mm axial difference from top to bottom. Visual comparison of the images highlights the difference in stability regimes between the two groups of cases. The argon diluted mixtures tested (Figure 7a-b) have highly organized wave fronts, with periodic intensity variation across the leading edge of the wave. The nitrogen diluted mixtures, Figure 7c-e, show less organized OH fronts, justifying the "moderately" unstable label applied to these cases. The scale of separation between alternating Mach stems and incident shocks vary significantly, as the triple points become stronger and more collected zones of heat release within the

wave-front. Additionally, as the level of nitrogen dilution increases (Figure 7(c) to (e)), the wave becomes more unstable. The distribution of the OH signal extends farther into the reaction zone and is less concentrated at the leading edge of the wave. These results are consistent with the observations of other researchers and serve to verify operation of the experiment.[14]

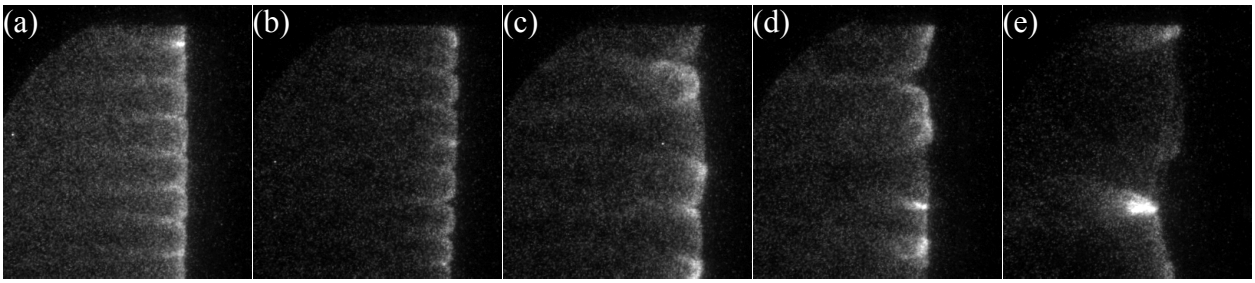

Figure 7: Chemiluminescence images in order of decreasing wave stability: (a) $2H_2-O_2-7Ar$, (b) $2H_2-O_2-9Ar$, (c) $2H_2-O_2-3.5N_2$, (d) $2H_2-O_2-4.6N_2$, (e) $2H_2-O_2-5.7N_2$. The presented images show a field of view that is 110 mm axially downstream from the start of the window and 122 mm vertically below the top.

A time series of chemiluminescence images acquired with the H_2-O_2-5.7N_2 test case is presented in Figure 8. Eight successive snapshots were captured as the wave propagated through the field of view. Panel (a) depicts the intersection of two triple points, followed by the expansion of a Mach stem in (b) with a closely coupled reaction zone. The transverse waves continue to separate in (c) until they intersect with a wall (top) and an adjacent wave (bottom) in (d). The development of a "keystone" structure is observed in (f) and (g); this is a spatial distortion in the lead shock, which appears as a region of low or high OH chemiluminescence signal separating reacted from unreacted gas.[11] When the lead shock engulfs this region of unburned gas it creates a region of high heat release within the wave front; this is seen in frame (h).

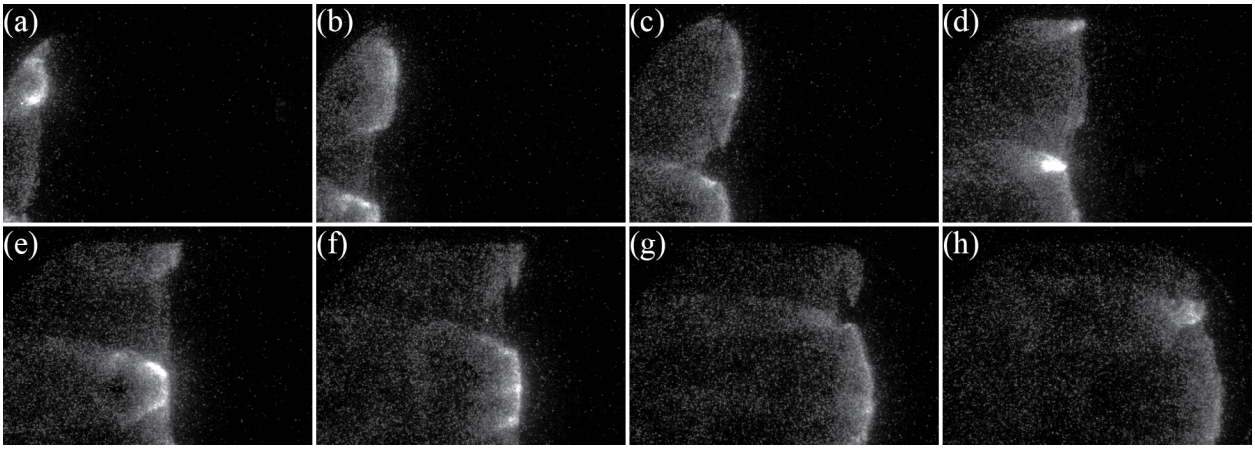

Figure 8: Sequential chemiluminescence images of $2H_2 - O_2 - 5.7N_2$. The images are taken 10.1 μs apart. The presented images show a field of view that contains the entire axially span of the window and is 122 mm down from the top.

IV. Conclusion

In this work, we have demonstrated operation of the GALCIT *Narrow Channel Facility* (NCF) at Purdue. The NCF was integrated into the facilities of Zucrow Labs to enable robust and versatile operation with the systems available. Results showed that the dynamically operated branched initiator is capable of producing a planar wave initiation, even in highly-diluted reactant mixtures. Five H_2-O_2 gas mixtures, diluted with argon and nitrogen, were tested each with decreasing levels of stability. All mixtures, once fully developed, displayed a wave speed within 4 % of U_{CJ}. Ultrahigh-speed chemiluminescence imaging of the reaction front showed distinct detonation structures that characterize the stability of the specific mixture composition. Results from this work build a foundation for the application of ultrahigh-speed optical diagnostics to support advanced understanding and new discoveries in detonation physics.

V. Acknowledgments

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