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## Performance Characterization of a Valveless Pulse Detonation Engine

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### Abstract

A valveless pulse detonation engine geometry has been partially evaluated on a direct-connect test stand at simulated inlet flight conditions to the combustor. The geometry utilizes a fuel/oxygen-enriched air initiator to initiate detonations in the main combustor and has been operated on ethylene, propane, and JP-10. The initiator has been operated at frequencies up to 100 Hz. The main combustor of the engine has only been evaluated up to 30 Hz operation due to a current design constraint which will be modified to allow higher frequencies in subsequent tests. The use of an initiator required the evaluation of the diffraction limits between the initiator exit and the main combustor. The successful use of an initiator to detonate a fuel/air mixture in a larger main combustor has been demonstrated. Furthermore, experimental data corroborated that tailoring the initiator to produce an overdriven detonation condition at its exit plane, enhanced the detonation transition into the larger combustor. Using imaging optical diagnostics, Mach reflections were observed at the combustor's wall just a few centimeters downstream of the initiator's plane. These appear to be the primary re-initiation mechanism for the re-establishment of fuel-air detonations for this geometry. Results show that a diameter ratio between the combustor and the initiator of at least 1.5:1 will allow successful operation for ethylene and propane. Single-shot diffraction tests evaluated combustor to initiator diameter ratios up to 1.58.

The specific impulse was computed from experimental measurements using both ethylene and propane fuels at various equivalent ratios from 1.0 to 1.5. The results showed Isp values ranging from 850 to almost 1200 seconds, but these relative low values were anticipated due to the

oversize initiator used in this study. Such a large initiator was required in order to characterize the aforementioned diameter ratios. Future tests will incorporate an optimally sized initiator, and extrapolation of the current data indicates possible Isp values as high as 1800 seconds with a stoichiometric propane – air mixture. This would indicate similar performance values to more conventionally valved PDE systems.

### Introduction

The interest in pulsed detonation engines (PDEs) has increased dramatically in recent years due to their high theoretical performance and wide range of potential applications'. Practical operation of these systems requires the use of fuels that have already gained acceptance/approval by the military and/or aviation industry, such as kerosene based Jet-A, JP-5, or JP-10. The use of such fuels has inherent difficulties since such fuel-air mixtures are often difficult to detonate<sup>2, 3</sup>, especially in a repetitive and reliable manner. Therefore various research teams are currently investigating the use of an initiator, which consists of a small tube or auxiliary combustor filled with mixtures highly sensitive to detonation as the means to initiate a detonation in a larger main combustor containing a less sensitive fuel-air mixture. Thus the importance of detonation diffraction or transmission from the small tube into a larger main combustor tube often arises.

Various initiator concepts exist and can vary from coaxial designs to transverse or splitter plate concepts just to name a few. Most concepts operate on fuel-oxygen mixtures while others utilize a blend of oxygen-enriched air as the oxidizer. Although the use of oxygen provides

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excellent reliability, repeatability, and a vary rapid ignition event, the minimization of the oxygen required is of paramount performance since it is treated as "fuel" for specific impulse ( $I_{sp}$ ) and specific fuel consumption (SFC) calculations and directly reduces the overall system performance. Thus, efficient coupling between an initiator and the larger combustor is of high importance.

The pulse detonation engine geometry under development at the Naval Postgraduate School utilizes a continuous air flow design, which does not require valves for the air supply to the combustion chamber. The geometry utilizes the initiator approach described earlier and is depicted in Figure 1. The initiator combustor operates on an oxygen-enriched fuel-air mixture to rapidly and reliably generate a detonation wave which can then be used to initiate the less sensitive fuel-air mixture located in the main combustor. The absence of a large valve on the air flow has permitted a convenient flow path to rapidly fill, detonate, and purge the combustion chamber at rates up to **100** Hz, but has also introduced difficulties into the initiation process due to lowered confinement conditions when compared to conventional PDE concepts which involve some type of valve on the air supply. A critical region of interest is at the initiator exit plane where the exiting detonation wave diffracts into the main combustor. The concern for this area of the system is the motivation for characterizing the effects of the diffraction condition between an initiator of diameter,  $D_i$ , and the main combustor of diameter,  $D$ , at the diffraction plane. The effects of diameter ratio ( $D/D_i$ ), mixture variation (overdrive), and varying degrees of confinement are being evaluated so that a more optimized condition can exist.

A large body of historical work has investigated the classical case of detonation transmission from a confined tube to an unconfined volume<sup>4</sup> for homogeneous mixtures. The well documented critical diameter value of **13** times the cell size (**h**) of the mixture for transmission of a detonation wave to an unconfined volume has been verified many times to hold true for most mixtures. The 13h value has been shown to be specifically valid for mixtures containing more irregular cell spacing, typically fuel/air mixtures with higher activation energies. Mixtures containing highly regular detonation cell

structure, such as argon diluted fuel/oxygen mixtures have been shown to often require a larger critical diameter than the **13h** rule, thus revealing the increased importance of wavefront structure during the diffraction processes in producing gas-dynamic hot spots for spontaneous reignition to occur. The increased irregularity in the cellular structure for fuel-air mixtures often aids in the adjustment to sudden expansion conditions and can be interpreted as possessing more levels of instability and therefore more modes by which spontaneous reinitiation may occur near a critical diameter value<sup>5</sup>.

Teodorczyk<sup>6</sup> and Oran<sup>7,8</sup> have looked at the reinitiation mechanisms of Mach reflections at a rigid wall from the propagation of a quasi-detonation in a obstacle-laden channel and an imparting spherical blast wave on a rigid wall, respectively. Both studies stressed the importance of the rapid reignition sites immediately behind the generated Mach stems at the wall. Murray<sup>9</sup> also demonstrated the importance of shock-shock and shock-wall collisions for different exit conditions at the diffraction plane, including tube bundles, annular orifices, and cylindrical diffraction. The reinitiation mechanism associated with the Mach reflections observed in those studies is extremely important for initiator concept utilized in the current engine. It also becomes increasingly important as the combustor diameter approaches the cell size of the mixture and few transverse waves exist to assist with adjusting to the expansion condition occurring at the diffraction plane. The reinitiation process for such conditions appears to be a very local process and the influence of the wave front structure" and reflection cannot be ignored during analysis.

Desbordes<sup>10</sup> and Lannoy<sup>12</sup> have investigated the effects of overdriving a detonation wave during diffraction from a smaller combustion tube to a larger volume. In both studies it was determined that a definitive benefit exists when a detonation wave is allowed to propagate into a less reactive mixture immediately before diffraction occurs, thus creating an overdriven condition in the less reactive mixture. Recently, Murray et al.<sup>13</sup> investigated the direct benefit of utilizing a fuel-oxygen driver section, an initiator, and propagating the generated detonation wave into a fuel-air mixture in order to generate the overdriven condition. Overall values of the effectiveness of

driver-receptor mixtures and diameter ratios approached 30 for some conditions indicating that a dramatic reduction in the required critical diameter for the receptor mixture. Thus, a combination of Mach reflections and overdriven conditions are the mechanisms which appear to dominate initiator transmissions on the scale of most PDEs and will likely be responsible for the successful application in such systems.

The operational cycle of the valveless PDE is shown below in Figure 2. The cycle begins with air flowing through the engine and purging the previous combustion products (A). Fuel is injected into the incoming air and flows into the main combustor (B). Near the end of the fuel injection event (C), a highly detonable mixture is rapidly injected into the initiator (D). The mixture in the initiator is ignited and a detonation wave forms (E). The detonation wave exits the initiator and initiates the fuel/air mixture residing in the main combustor (G). After the detonation exits the main combustor, a series of rarefaction waves reduce the pressure inside of the combustor and the combustion products are purged (H). The process is then repeated.

Immediately after the detonation wave from the initiator diffracts into the main combustor, a combustion-driven shock wave, which transitions into a decaying blast wave, begins to propagate upstream into the incoming air stream. This propagation can be eliminated if the total pressure of the incoming air is sufficiently high and results in a choke point somewhere in the isolator, thereby producing a supersonic flow regime immediately downstream of this point. The current test program only evaluated subsonic flow conditions and limited the isolator flow Mach number to 0.9. Future testing will explore the supersonic isolator mode.

### Experimental Setup

The multi-cycle PDE consisted of four fuel-air inlet arms discharging into a common inlet manifold. Vitiated air, up to 550 K, was distributed into the four arms where fuel was then injected using either high-speed solenoid valves or liquid fuel injectors from Sturman Industries. The fuel/air mixture was then allowed to co-flow around the initiator, through a 5 degree transition ramp, and then into the main combustor which

was 1 meter in length and had a diameter of 0.1016 meters. The initiator could be moved to different axial positions along the 5 degree transition ramp to determine where the expansion area becomes too large for a detonation wave to transition to the main combustor.

The initiator was a 320.6 mm long stainless steel chamber with an exiting internal diameter of 44.45 mm and used an ethylene/air/oxygen-enriched mixture to rapidly and reliably form a detonation. The overall length/volume was larger than necessary due to the requirement that the initiator exit plane needed to be positioned at various axial locations. The initiator geometry has been previously developed and has demonstrated operation on ethylene, propane, and JP10.<sup>14</sup> The volume of the initiator was 0.000475 m<sup>3</sup> and the volume of main combustor was 0.008533 m<sup>3</sup>, resulting in a total engine volume of 0.00858 m<sup>3</sup>.

### **Diagnostics**

High frequency Kistler 603B1 pressure transducers and type-K thermocouples were placed along the PDE to monitor detonation/shock wave speeds and engine inlet conditions. Transmission measurements were made at two locations with a 3.39  $\mu\text{m}$  He-Ne laser and an infrared diode to determine the proper timing of the fuel delivery and the resulting fuel mass fraction. The transmission ratio received from the diode was used in conjunction with the Beer-Lambert law, Equation 1, to determine the partial pressure and eventually the mass fraction of the fuel in the mixture at that time of transmission.

$$T = e^{-\alpha ax} \quad (1)$$

Where T is the transmission ratio obtained from the attenuation measurements, x is the transmission path across where the attenuation occurred and  $\alpha$  is the absorption coefficient provided in various references<sup>18,19</sup> for various fuels. Given this information, the partial pressure p can be calculated and subsequently used to determine temporal fuel/air ratios in the main combustor as well as the spatial distribution of fuel along the combustor. Ideally the end of the fuel injection charge would be located precisely at the initiator diffraction plane at the moment the initiator detonation wave diffracts into the main combustor.

Detonation wave diffraction conditions at the initiator/main combustor interface were also characterized on a single-shot detonation facility using high-speed Schlieren and CH\* chemiluminescence imaging which utilized a 10nm FWHM interference filter centered at 430nm.<sup>15</sup>

Thrust measurements were made for the multi-cycle tests by utilizing a spring/damper deflection system and a linear displacement indicator. An average displacement value during the tests was then correlated to an average thrust.

## **Results**

### **Single-Shot Tests**

The initial testing for the valveless geometry began approximately one year ago on a single-shot detonation facility which allowed optical access to the diffraction plane. The 2" x 2" optical port allowed high speed shadowgraph measurements to be made in conjunction with single-image CH\* chemiluminescence images. The geometry was representative of the valveless configuration and allowed multiple diffraction ratios to be characterized. The experimental setup for those tests and sample CH\* images are shown below in Figure 3.

All tests were performed at a nominal pressure and temperature of 100kPa and 283 K, respectively. The primary re-initiation mechanism after diffraction was observed to be due to the strong Mach reflections resulting from the residual shock of the decaying blast wave reflecting from the outer wall. The increased heating and associated chemical activity behind the Mach stem provides the rapid energy release required for re-initiation. It is believed that if the exiting detonation wave from the initiator can be tailored to produce an overdriven detonation, the transmission across the diffraction will be substantially enhanced. A schematic of what is believed to occur is shown in Figure 4 and appears to agree with computational results from Oran and Kailsanath<sup>7,17</sup>. Caption (c) in Figure 3 shows the CH\* emission commonly found to correspond with the near wall Mach stem reflection and the resulting increase in local reaction rate. This behavior was normally observed at distances less than 1.0 D<sub>i</sub> from the diffraction plane. Figure 5 summarizes the successful and unsuccessful test conditions for which detonation transmission

occurred for the ethylene-air mixtures for the single-shot cases. The results indicate that for an initiator operating equivalence ratio of 1.0, a diffraction ratio of 1.8 should result in a successful detonation transition to the main combustor.

### **Multi-Cycle Tests**

The first series of tests on the multi-cycle engine were performed to verify fuel delivery and equivalence ratios. The 3.39 micron transmission measurement was used at both the initiator diffraction plane and at the combustor exit to determine fuel arrival and fuel mass fraction. The tests verified successful operation of the liquid and gaseous fuel injectors. Transmission results for 80 Hz operation on liquid propane are shown in Figure 6. The square TTL trace represents the injection command for the initiator and the equivalence ratio trace is that for the propane/air mixture as it entered the main combustor. The variation in equivalence ratio could be minimized by tailored injection of each fuel injector, but tended to become more non-uniform temporally as the operational frequencies increased. Gaseous injection of ethylene and propane tended to be much more consistent resulting in more uniform fuel mass fraction along the combustor.

Two important gas dynamic processes occurring within this engine are the dynamic fill response and the forward/aft propagation of disturbances. Characteristics for the baseline case of D/D<sub>i</sub>=1.25 is presented in Figures 7 and 8. Figure 7 shows the local Mach number versus area for a mass flow of about 0.30 kg/s. Since the first portion of this test program was to evaluate the subsonic isolator operation of this engine, any additional mass flow would force the isolator to choke locally and produce a supersonic flow region immediately downstream of that point. The condition depicted in Figure 7 is for an air mass flow rate of 0.30 kg/s and shows the isolator Mach number approaching 0.95 and then decreasing as the cross-sectional area downstream of the isolator increases. Figure 8 shows the behavior of both the forward propagating and rearward propagating disturbances for a M<sub>ISOLATOR</sub>=0.9 condition of propane/air at an equivalence ratio of 1.2 and x=0 being defined as the initiator exit. The right-running red trace depicts the propagation of the propane/air detonation towards the tube exit at the detonation velocity, V<sub>CD</sub>. Immediately behind the

detonation front are a series of rarefaction waves which gradually reduce the post-detonation pressure to a lower value. Once the detonation wave exits the tube, a series of rarefaction waves begin to propagate upstream in order to reduce the pressure in the combustor. Only the leading rarefaction wave is depicted in the figure and is shown to propagate at the local speed of sound of the products. This and subsequent expansion waves will eventually catch up to the forward running shock wave, depicted as a left-running blue trace, initially propagating upstream at about  $V_{SH}=450$  m/s in the laboratory reference frame. The propagation of the forward running shock wave eventually ends and the combustor is purged with the incoming air. The process repeats for each detonation cycle. It can be seen that the isolator length for a valveless design operating in a subsonic mode and an isolator Mach number of 0.90 would need to be approximately 0.5 meters long for a 1 meter long main combustor. If the combustor is shorter than this length, the forward propagating disturbance could result in an inlet problem. During this testing, disturbances were prevented from propagating further than 78 cm upstream due to a mass metering venturi.

The engine has been evaluated over a diffraction range of 1.25 to 1.58 and operated on both ethylene and propane fuels from stoichiometric to an equivalence ratio of 1.5. It is expected that the upper limit to be tested will be a diameter ratio of 2.25. It can be seen that ethylene/air mixtures at an equivalence ratio of 1.2 have successfully diffracted for all diameter ratios tested to date. Propane has only recently been evaluated, and will continue to be investigated over the up coming months.

### Performance Measurements

Performance calculations were made for full-fill tests which exhibited nearly 100% successful detonations. Although certain runs did involve occasional “misses” or deflagration events, an adequate portion of the run profile was executed to achieve successful quasi-steady state conditions. A sample pressure and thrust dataset for a propane/air run at a target equivalence ratio of 1.05 is shown in Figure 9. The last pressure transducer before the combustor exit is shown along with the displacement transducer which recorded the displacement of the engine cradle

which was then correlated to a thrust force. Individual detonation impulses can be seen to “scallop” the force measurements which appear to increase to a quasi-steady state value. The measured thrust on the stand is gross thrust, and therefore includes the thrust contribution due to the purge and fill processes associated with this design.

The specific impulse calculations were made using the gross thrust measurements and net thrust corrections were made by subtracting out the thrust contribution between cycles. The corrections were approximate due to the subjective separation between fill, purge, and blowdown durations. The gross thrust values typically were reduced by 3-4% for the 20 Hz operation at a mass flow rate of 0.32 kg/s. As the operational frequency is increased, the contribution is further reduced. The fuel-based specific impulse was calculated two ways, represented by Equations 2 and 3. First, by only accounting for the fuel in the main combustor and secondly by also accounting for the fuel and extra oxygen used in the initiator.

$$I_{SPf} = \frac{T_{GROSS} / f}{m_f g} \quad (2)$$

$$I_{SPf} = \left( \frac{T_{GROSS} / f}{(m_f + m_{f\_INIT} + m_{O2\_INIT}) g} \right) \quad (3)$$

The results for selected propane/air cases are shown in Figure 10. It can be seen that the specific impulse values appear artificially higher, as expected, when the initiator reactants are ignored. The second calculation, which includes all of the fuel and auxiliary oxygen used in the engine, is obviously the more accurate representation of the total system performance with the relatively large initiator contribution. The theoretical line presented on Figure 10 represents the extrapolated performance if the total auxiliary oxygen requirement for the initiator was reduced to 1% of the total engine volume. Since this would substantially reduce the amount of fuel required for the initiator as well, the increase in specific impulse is dramatic.

If the gross thrust is corrected and a net thrust value obtained, a comparison to a conventional valved PDE system may be

attempted. Assuming the aggregate detonation duty cycle is 5% for 20 Hz operation, a 9.69 N value must be subtracted from the gross thrust value to determine the net thrust value. The average net thrust for an equivalence ratio of 1.0 was therefore calculated to be 222.49 N and divided by the 20 Hz frequency for that run resulting in an impulse of 11.12 N per detonation event.

This value can be compared to a test case evaluated at Caltech for a stoichiometric propane-air mixture detonated with a propane-oxygen initiator "plug" which was 6% by volume<sup>20</sup>. The initial conditions for that test were 100 kPa and 297 K. The impulse per unit volume,  $I_v$ , was determined to be 1201 kg/m<sup>2</sup>-s. From this value, the Caltech data would indicate an impulse of 10.31 N, or 7.37% below our calculated net impulse. This is surprising since the Caltech initiator volume was slightly larger than used during these tests. The increased impulse could be caused by additional fuel delivery upstream of the initiator discharge plane due to a solenoid valve staying open longer than expected. In order to eliminate this uncertainty in the future, current, voltage, and pressure monitors will need to be installed on each high speed solenoid valve to determine the actual fuel injection duration for each cycle as well as the location of the fuel/air mixture interface.

Another contributing factor to the increased net impulse observed is due to the increased amount of working fluid compressed "upstream" involved per detonation event. No attempt was made to account for this effect at this time, but this correction would obviously show the two results in better agreement.

### Conclusions and Future Work

The generation of strong Mach stem reflections downstream of the diffraction plane of the initiator combustor were found to be a reliable reinitiation mechanism for the transmission of a detonation wave into a larger combustor over the range of diffraction ratios evaluated to date. So far, diffraction ratios up to 1.58 have been successful with ethylene/air mixtures and propane/air mixtures have been successful diffracting up to a 1.43 ratio. The reliable generation of Mach stems along the wall

downstream of the diffraction plane for coaxial initiators/combustors should be a valuable mechanism to take advantage during engine design since they do not depend directly on cell size, but on the strength of the exiting shockwave and the physical diffraction condition. The sensitivity of the mixture to reignition can be correlated to the detonation cell size of the reactants used.

The ability to isolate the incoming air flow from the detonation products has been shown to rely heavily on the isolator Mach number and combustion chamber length. Although only subsonic isolator Mach numbers were evaluated during this portion of the test program, sonic or supersonic values corresponding to total pressure of 100 psi or higher will likely provide total inlet isolation from the post detonation pressure and will be evaluated in the next phase of this research.

Specific impulse calculations for the valveless geometry operating on propane/air ranged from 850 to almost 1200 seconds over an equivalence ratio range of 1.5 to 1.0 respectively, but these relative low values were anticipated due to the oversized initiator used in this study. Such a large initiator was required in order to characterize the aforementioned diameter ratios. Future tests will incorporate an optimally sized initiator, and extrapolation of the current data predicts possible Isp values as high as 1800 seconds with a stoichiometric propane – air mixture. This would indicate similar performance values to more conventional valved **PDE** systems. The minimization (<1% by volume) or elimination of auxiliary oxygen for this system will be critical for it to remain competitive with existing propulsion systems. Although it is believed this hurdle can be overcome, it will be difficult. Additionally, the introduction of an exhaust nozzle to the system will introduce further challenges, but may provide an additional performance increase due the thermal-to-kinetic conversion of energy through the nozzle while providing some degree of back pressurization for altitude considerations.

### Nomenclature

D	Combustor Diameter
$D_i$	Initiator Exit Diameter
$g$	Gravity, 9.81 m/s <sup>2</sup>
$m_f$	Mass of Fuel in Main Combustor
$m_{f\_INIT}$	Mass of Fuel in Initiator
$m_{O_2\_INIT}$	Mass of Extra Oxygen in Initiator
P	Partial Pressure of Fuel
T	Transmission Ratio
$T_{GROSS}$	Gross Thrust
$T_{NET}$	Net Thrust
X	Path Length
$V_{CJ}$	Chapman Jouget Detonation Velocity
$\lambda$	Detonation cell size

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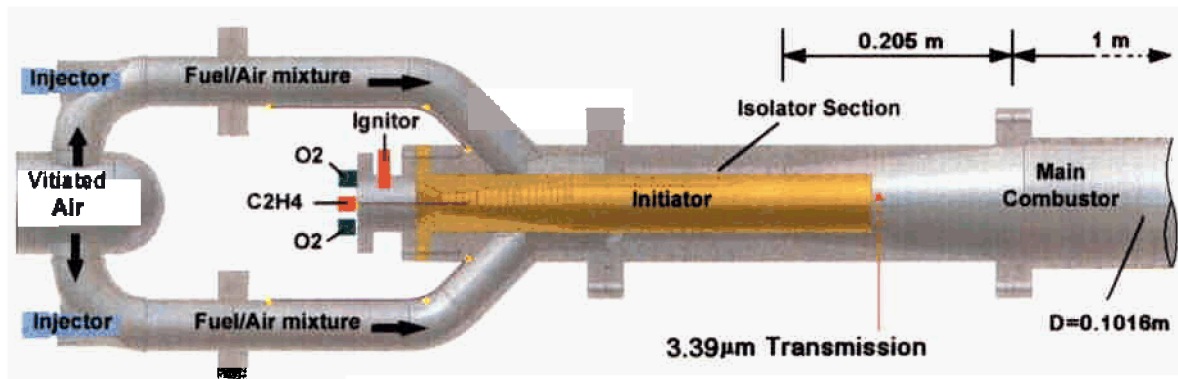


Figure 1: Valveless PDE Configuration

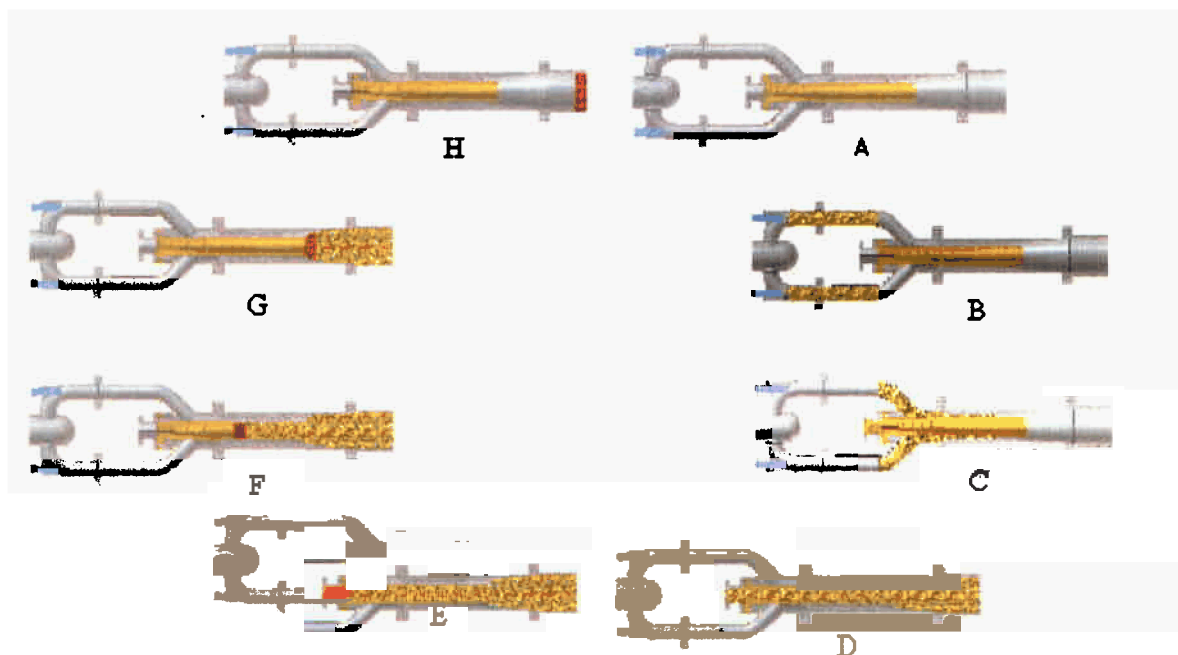
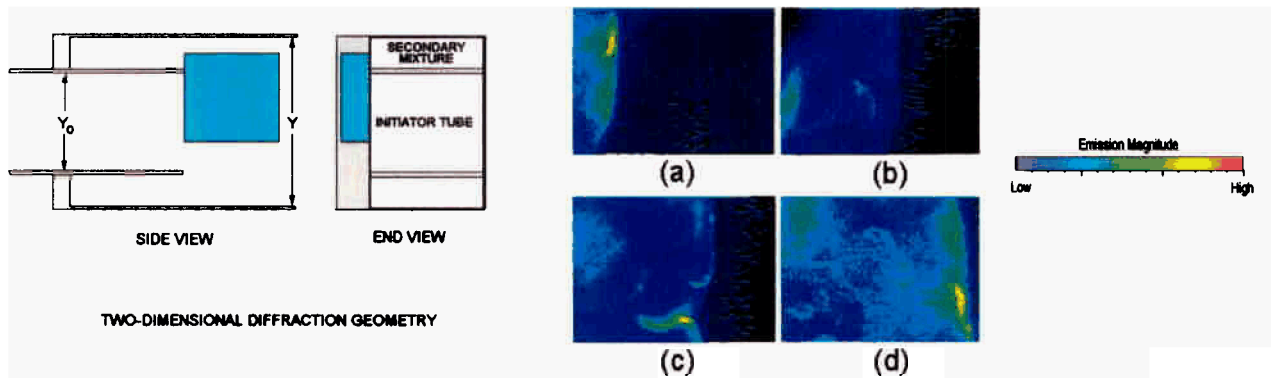
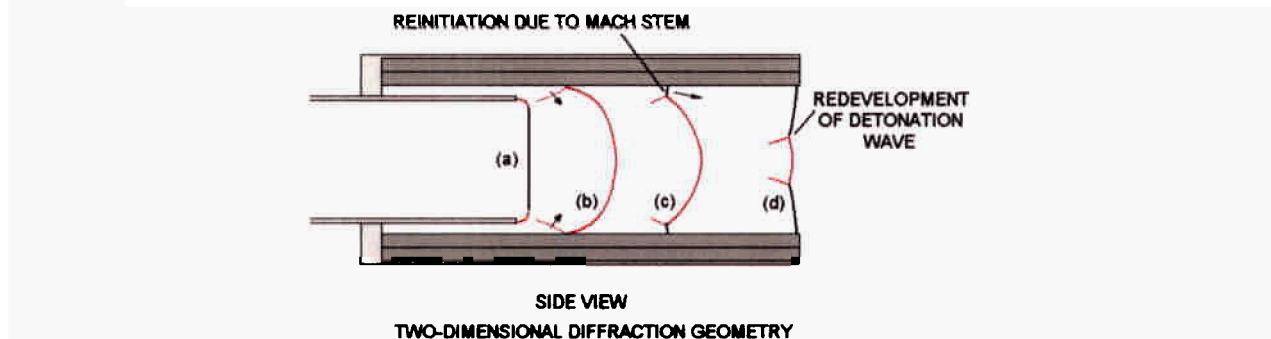


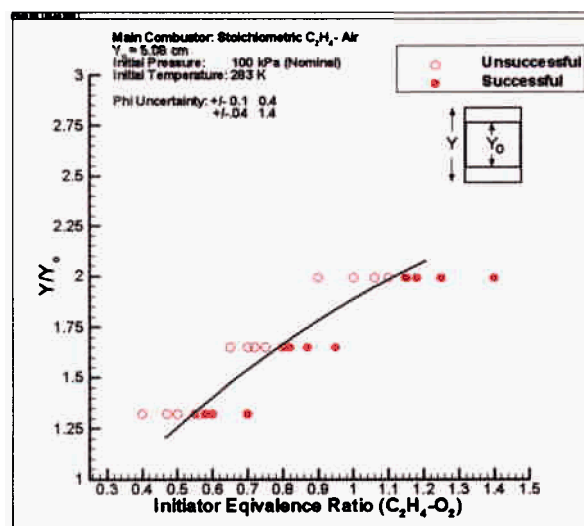
Figure 2: Operational Cycle of a Valveless PDE



**Figure 3:** Experimental Setup for Single-Shot CH\* Images (left) Sample Images at (a)  $t=15 \mu s$  (b)  $t=22 \mu s$  (c)  $t=29 \mu s$  (d)  $t=36 \mu s$  for a Diameter Ratio of 1.33.



**Figure 4:** Representation of the Observed Detonation Diffraction/Reinitiation Process



**Figure 5:** Results for the Two-Dimensional Single-Shot Diffraction Tests

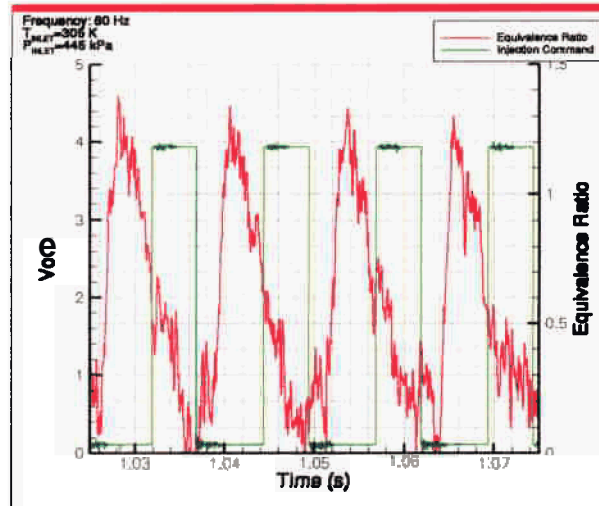


Figure 6: Timing and Equivalence Ratio vs. Time for Propane/Air Injection

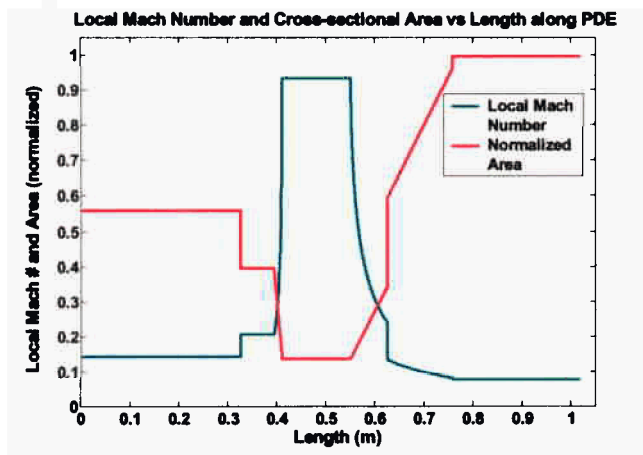


Figure 7: Local Mach Number and Cross-sectional Area vs. Length along PDE

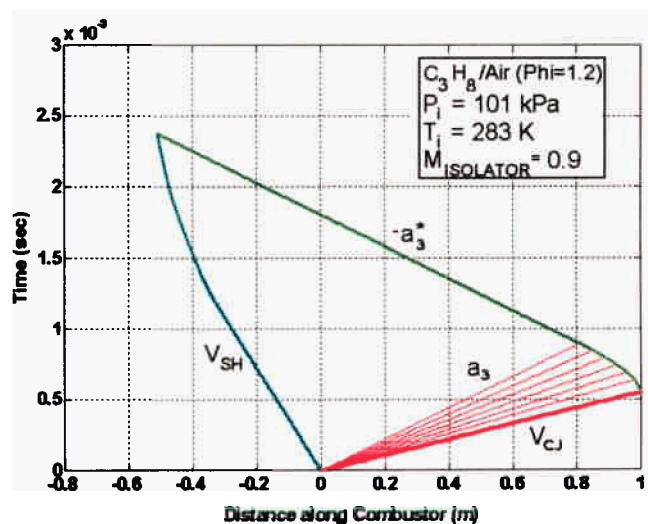


Figure 8: x-t Diagram of Forward and Rearward Propagation of Disturbances

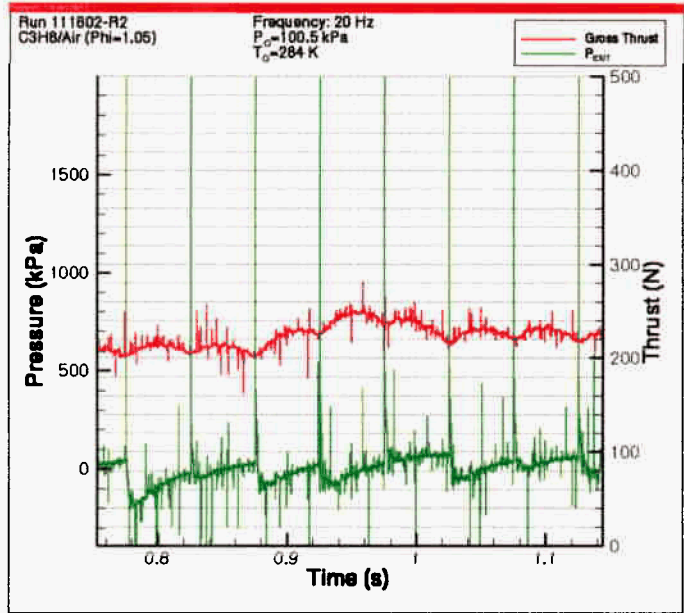


Figure 9: Sample Thrust and P<sub>EXIT</sub> Data for Propane/Air Test at a Target Phi=1.05

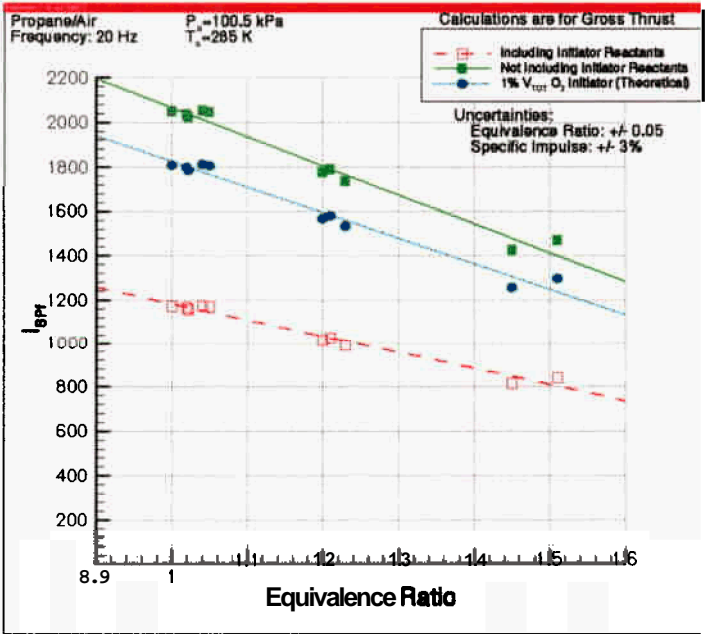


Figure 10: Specific Impulse versus Equivalence Ratio for Propane/Air Runs (Full Fill)

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