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Investigation Of Transient Plasma Ignition For Pulse Detonation Engines

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Reduction of auxiliary oxygen amounts currently used in Pulse Detonation Engines (PDEs) is necessary to compete with existing Ramjet technologies. This paper investigates a Transient Plasma Ignition (TPI) system and finds that this technology enables the complete removal of any auxiliary oxygen requirements of current PDE systems. TPI was tested and compared with a traditional capacitive discharge spark ignition system within ethylene/air mixtures under dynamic fill conditions. Successful operation was achieved at up-to 40Hz repetition rates. Ignition delay times, Deflagration-to-Detonation transition (DDT) distances and DDT times, detonation wave speeds, and detonation initiation success rates were measured and analyzed for various mass flow rates, for various ethylene-air mixtures, and for various lengths of turbulence generating Schelkhin spirals. A transient plasma dual-electrode concept was also investigated and analyzed.

Results show that TPI system is more effective than conventional spark ignition systems. The TPI system shows near 20% improvements to DDT distances and up-to 2.5 reduction factor in DDT times. In addition, at high flow rates, where the flames normally extinguish when employing the spark ignition system, the TPI system was able to ignite mixtures and effectively initiate detonation waves. Detonation initiation success rates greater than 94% were obtained at cycle frequencies of up-to 40Hz. Further work is required to discern the TPI system sensitivity to back pressures; additional instrumentation is required to determine axial variations in equivalence ratio.

I. INTRODUCTION

A. PULSE Detonation Engine Ignition Technology

Effective and reliable detonation initiation in fuel/air mixtures is one of the most important challenges in the development of a practical PDE [1-7]. There are 3 different methods of initiating a detonation wave, by Direct Initiation, through Shock-Induced Initiation, and by a Deflagration to Detonation Transition (DDT) process [8]. It is the latter, which was investigated.

1. Direct Initiation Method

To directly initiate and detonation wave, a critical minimum energy deposition must occur in a very short time (compare to chemical kinetic reaction times). This process usually requires the use of an explosive charge to effectively deliver the large energies required [8, 9]. Another method that has had some success is to focus a set of high- powered pulsed laser beams into a point [10]. Neither of these methods is practical for a multi-cycle PDE. For

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instance, the use of explosive charges at PDE frequencies would create prohibitive mass requirements and complex explosive management issues.

2. Shock-Induced Detonation

In this method high pressure and temperature behind shock waves start the mechanical reaction in the mixture behind the shock wave and if critical pressure and temperature are reached behind the shock, a detonation wave is initiated [8, 9, 11]. This method has been proven to be very effective in recent years. For PDEs, only the DDT method and the Shock-Induced Method or a combination of the two is practical [1, 6, 7].

Two shock-induced detonation techniques have been studied in significant detail: shock focusing and the initiator (pre-detonator) approach. In shock focusing, geometry is used to manipulate, collide or otherwise enhance shock or shocks in order to accomplish DDT. Extremely geometry dependent, hard to generate reliably and highly dynamic, shock focusing has achieved limited success [12, 13].

A hybrid approach is where DDT is used in a fuel/oxygen mixture to produce a shock that in turn induces a detonation in a less sensitive mixture on a bigger main combustor. The concept of this detonation-to-detonation unit is to use a small tube (1% or less volume of the main combustor's volume), which is filled with highly sensitive mixture, such as ethylene/O_2 or JP-10/O_2 [14, 15]. A detonation is rapidly created in the "initiator" and discharged into the main combustor where a less sensitive mixture awaits, such as ethylene/air or JP-10/air. Effective transmission is key for success and is defined as one in which the detonation wave exiting the smaller combustor overcomes the diffraction process and continues propagating into the less sensitive fuel-air mixture as a detonation wave. An effective transmission also results when a detonation wave exiting the initiator tube fails during the diffraction process while entering the main combustor due to the diffraction process weakening the leading shock, but due to reflection and/or shock focusing/reflection processes which may occur in the gas dynamic flow downstream of the initiator tube, a detonation re-initiation process occurs and thus an "effective" transmission occurs. The re-initiation process is therefore due to the production of local hot spots where detonation re-initiation occurs [8, 11, 14, 15].

3. DDT Method

Deflagration to Detonation transition (DDT) is the process by which a laminar flame changes propagation mechanisms and eventually develops into of a self-sustaining detonation wave. DDT can be summarized as follows: (1) Ignition and wave propagation. (2) Flame wrinkling, turbulence onset and dramatic increase in burning rate. (3) Increased burning rates increase flow velocity ahead of the mixture due to expanding gases. Unsteady compression waves ahead of flame front increase temperature sufficiently to produce an acceleration effect on reaction rates. Shock front formation occurs due to coalescence of compression waves. (4) Detonation onset, "explosion in an explosion", where there is an abrupt appearance of explosion centers or "hot spots" in the shock. (5) The detonation wave propagates, if successful, developing into a pseudo-steady, self-sustaining wave traveling at the Chapmann-Jouguet (CJ) conditions [8, 11, 16].

There is a significant and comprehensive database of research PDEs that employ this method of detonation initiation. This method uses low energies for ignition and has been employed with wide range of mixtures. Internal DDT obstacles are often required for achieve detonation within a short tube unless there is the use of auxiliary or supplementary oxygen beyond the levels of that found in air. It is important to note that the use of DDT obstacles has significant impact in PDE performance as it does inherently create drag losses and mass penalties [17].

B. Transient Plasma Ignition (TPI)

Transient Plasma Ignition is at the forefront of research efforts for propulsion systems. In TPI, a pseudo-spark (corona) discharge in the tens of nanoseconds time scale can be applied to quiescent or flowing mixtures [18, 19].

Corona discharges (the portion of an electric discharge before the onset of the low-voltage, high current arc discharge) are plasmas that are in a transient, formative phase [19]. These discharges have the potential to overcome many of the limitations of conventional electric discharges, such as the Capacitive Discharge Spark, and laser discharges for reasons that include: (1) better energy coupling into gaseous mixtures because the cross-section for dissociation and ionization of large hydrocarbon chain molecules more nearly matches the electron energy distribution function; (2) lower losses through lower radiation, lower anode and cathode losses, and lower gas dynamic disturbance formation; (3) there are many streamers, each of which has a similar energy content, as opposed to a single, unnecessarily large and intense arc, which in turn can initiate combustion in a larger volume and (4) the size and shape of the ignition volume can be tailored using the geometry of the anode and cathode. The latter can be part of the internal flow geometry of the PDE [18].

With recent advances in pulsed power electronics, such discharges can be produced efficiently in systems of reasonable cost, size and mass. Gundersen's group at USC, have developed energy-efficient transient plasma ignition systems appropriate for PDE research. Preliminary results have demonstrated that TPI reduced ignition delay by at least factor of 3 within quiescent atmospheres; signaling significant promise in the use of the technology for improvements in ignition reliability, effective DDT and performance.

C. Motivation

The motivation of this work is to evaluate TPI technology for PDE, with the objective to determine the possibility of the complete removal of the auxiliary oxygen requirements in current PDE technology. As shown in Figure 1, the NPS valveless PDE design utilizes continuous airflow through the engine flow path and does not modulate the airflow through the use of valves as with most designs. The proposed design, will replace the initiator section, the ignitor, and the Oxygen high-speed valves with a TPI system as shown in figure 2.

Current experimental estimates for the specific impulse, Isp, performance of this PDE configuration show significant potential for PDE technology to become competitive with current Ramjet technology.

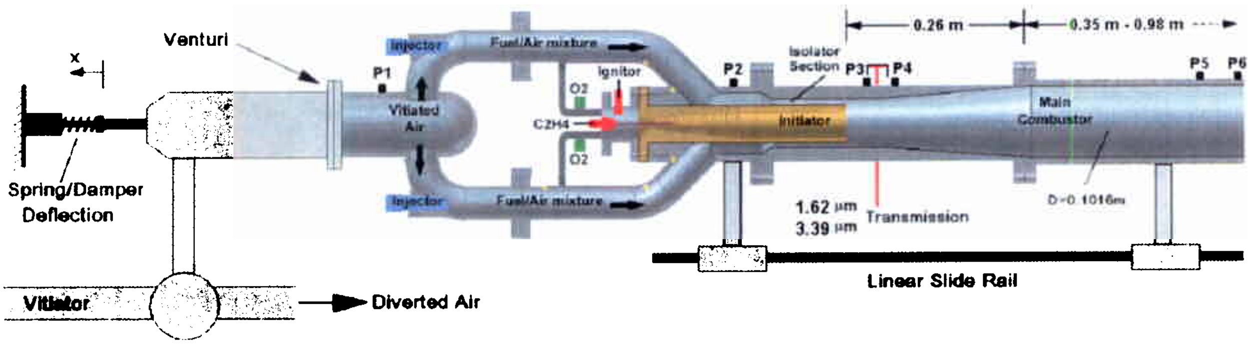

Figure 1. Current NPS Valveless PDE Design with conventional spark ignition system.

By analyzing Eq. 1, one can surmise that specific impulse, Isp, performance improvement can be achieved by the reduction or elimination of the requirement of initiator auxiliary (supplementary) oxygen, $m_{O2\ Aux}$, in the denominator.

$$I_{sp_f} = \frac{F}{m_{fuel}g} = \frac{F}{(m_{fuel} + m_{Initiator\ fuel} + m_{O_2\ Aux})g} \quad (1)$$

From Kailasanath's [1] and Paxons' [20] computational work, PDEs show significant advantages in Mach numbers below 3.5 over Ramjet technologies. Experimental results from NPS' valveless PDE design with a conventional spark ignition and auxiliary O_2 can be extrapolated to make predictions without any O2 addition and show that Isp values between 1500 s to 1800 s at a simulated flight Mach number of 2.1 are achievable [17]. These results agree very well with Paxons' computations.

The agreement between NPS' extrapolated results and Paxons' computational predictions motivated us to solve the problem of eliminating the excess oxygen requirements in current PDE technologies. The next sections cover the experimental apparatus designed to enable the integration of a transient plasma ignition system into a valveless desgn pulse detonation engine. The DDT performance of TPI system is also compared to that of a Capacitive Discharge Spark Ignition (CDSI) system. An additional concept that utilizes two TPI electrodes for ignition is discussed and evaluated.

II. EXPERIMENTAL SETUP

The PDE combustor had a 3-inch inner diameter to allow for at least 2 detonation cell sizes (Dia. $\geq 2\lambda$,) within the combustor for a variety fuel-air mixtures, such as ethylene/air, propane/air, and JP-10/air mixtures [9].

Due to its modular design as shown in figure 2, several configurations were possible and employed. The design called for an 8 in long head-end segment and 6 other segments: two segments each of 3, 6 and 9 in long. Each of the segments is able to accommodate a Schelkhin spiral if so desired, therefore allowing the total length of the schelhin spiral to vary between 3 in and 36 in long. These spirals are made of 0.125 in. diameter treated stainless steel wire, with a spiral coil spacing of 1 tube diameter as this configuration has been proven near-optimal for DDT obstacle spacing by past PDE research [21,22].

A. Test Configurations

1. Capacitive Discharge Spark Ignition Configuration

The PDE combustor configuration tested using a CDSI system had an overall combustor length of 1.13 m with a 0.914 m long Schelkhin spiral. In this configuration the PDE combustor was instrumented with four K-Type thermocouples (used to record ethylene, air, engine inlet and outlet temperatures); seven high-speed pressure transducers were used to record combustor pressures and wave speeds. This configuration is shown in below:

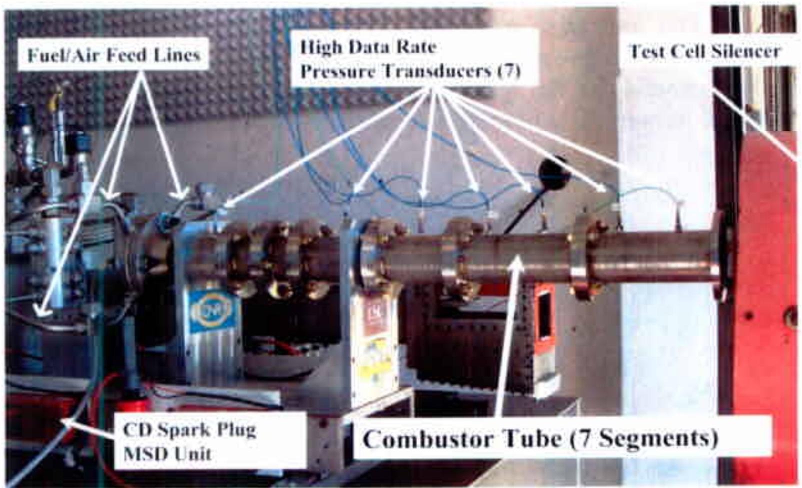

Figure 2. Capacitive Discharge Spark Ignition System Configuration

One Champion RN12YC spark plug was installed in the combustor's head flange center. The spark plug was powered by a MSD 6-Series ignition system.

2. Transient Plasma Ignition Configuration

The transient plasma pulse generator is designed to deliver pulses of 70 kV to 100 kV with currents ranging between 450 A and 600 A, all within 50 to 100 nanoseconds. In order to avoid occasional arcs, the output impedance of the generator is matched to the load, so peak currents are limited to twice the operating current. The pulse shape is relatively unimportant as long as both the voltage and current are delivered simultaneously. The rise time, repetition rate, and reliability requirements can be met using pseudo-spark switch. The final pulse amplitude is achieved by using a pulse transformer [19]. Figure 3 shows an schematic of this system and Fig. 4 shows a typical TPI system's pulse profile.

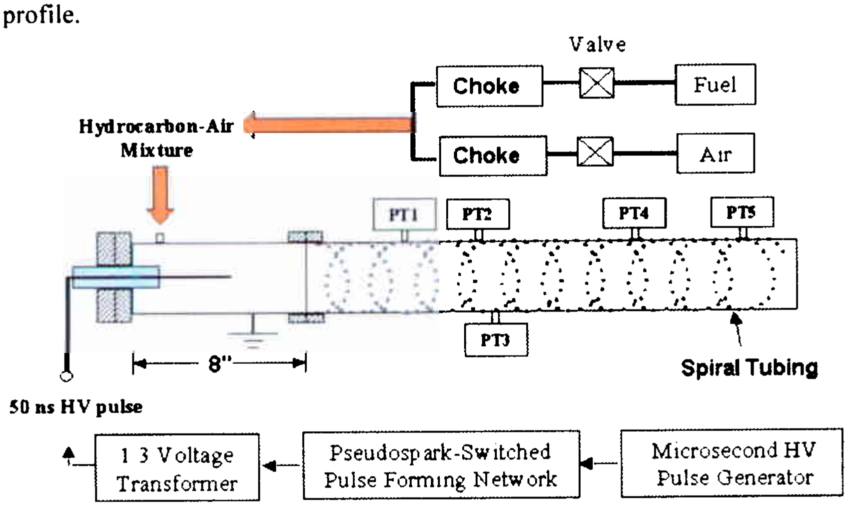

Figure 3. Schematic of a PDE with a Transient Plasma Ignition System.

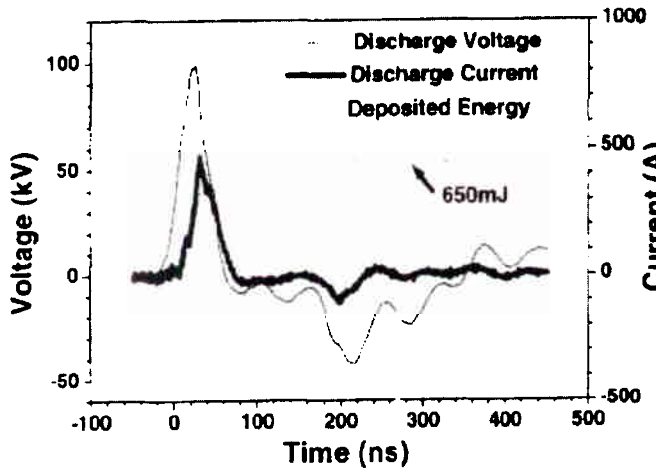

Figure 4. Typical Discharge Voltage and Current Pulse Profiles with a computed Deposited Energy Profile.

a. Single Electrode TPI Configuration

This PDE combustor configuration was almost identical to the one described above for the CDSI system. The one difference was the replacement of a spark plug with a 76 mm long, 4 mm diameter stainless steel electrode located at x = 0 (L1 configuration).

b. Dual Electrode TPI Concept and Configurations

The concept of using a second electrode to decrease DDT distances and/or DDT times was implemented in a set of 7 configurations. The second electrode was placed upstream of the onset of detonation. It was envisioned that a second transient plasma discharge triggered at an appropriate time after the first discharge, would result in the acceleration of the DDT process.

Seven configurations utilizing the dual electrode TPI concept were tested. In six of the configurations, the first electrode spanned a length of 3 in (from x = 0 to 3 in), this electrode configuration was called L1. The second electrode also 3 in in length was placed at x = 10.5 in (electrode configuration L2). This second electrode was also relocated further downstream to an x location of 19.5 in (electrode configuration L3). In addition, the spanned length of the Schelkhin spirals was varied. The PDE combustor with electrodes at locations L1 and L3 is shown below in Fig. 5.

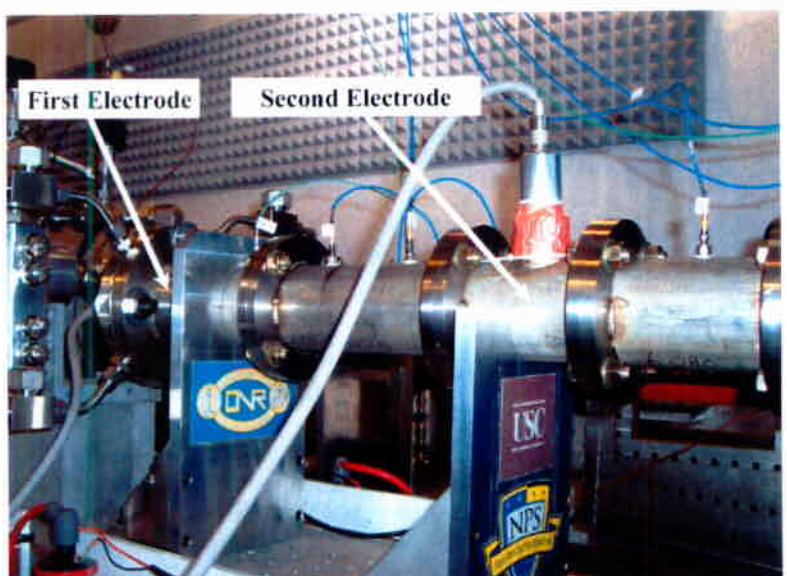

Figure 5. Dual TPI System Configuration (L1 and L3 configuration)

B. Test Matrix

For the CDSI system, three independent variables were investigated: mass flow, mixture equivalence ratio and the length of internal obstacles required for successful DDT. Table 1 lists the specific conditions tested for each parameter.

A similar test matrix, shown in Table 2, was applied for the TPI system tests. In which two additional variables were investigated: second electrode ignition trigger delay and second electrode location.

Table 1: Capacitive Discharge Spark Ignition Test Matrix

Variable	Values Investigated	Units
Mass flow	0.025, 0.050, 0.075, 0.1,0.2, 0.3, 0.4, and 0.5	kg/s
Equivalence Ratio	0.8, 0.95, 1.0, 1.025, 1.05, 1.10, and 1.2	N/A
Internal DDT Obstacle Length	Minimum for DDT	in
Ignition Delay	measured	ms

Table 2: Transient Plasma Ignition Test Matrix

Variable	Values Investigated	Units
Mass flow	0.025, 0.050, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, and 0.5	kg/s
Equivalence Ratio	0.8, 0.95, 1.0, 1.025, 1.05, 1.10, and 1.2	N/A
Internal DDT Obstacle Length	Minimum for DDT	in
Ignition Delay	measured	ms
Second Electrode Ignition Trigger Delay	0.35, 0.45, 0.50, 0.55, 0.65, 0.70 and 0.75	ms
Second Electrode Location	10.5 or 19.5 (locations L2 and L3)	in

III. RESULTS AND DISCUSSION

Figure 6 shows typical combustor pressure traces from the high-speed pressure transducers. These traces were used to determine detonation success rates, detonation wave velocities, ignition delay times, DDT distances, and DDT times.

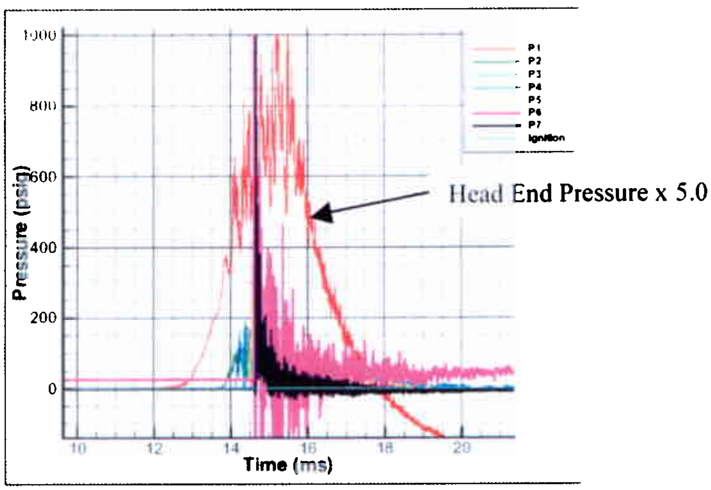

Figure 6. Capacitive Discharge Spark Ignition System - Test Run 6

Detonation velocity, V_{det}, between transducers n and n+1 was determined using Equation (2), where Δx is the distance between two high-speed pressure transducers, and Δt is the time delay between two vanNeumann pressure peaks measured from trace plots similar to those shown in Fig. 6. The ignition delay, defined here as an initial pressure rise of 1 atmosphere at the combustor's head-end, was determined from the pressure traces recorded from transducer #1, since detonation waves were only formed near the aft-end of the combustor, it was possible to significantly increase the sensitivity of transducer #1 (to 10 psi/volt as compared to 200 psi/volt for the rest of pressure transducers.). Further analysis of pressure traces' magnitude and location yielded DDT location and DDT time estimates. Due to the volume of the data, 1 s of data for 8 channels at up-to 1MHz sampling rate = up to 8 million data points per run, data analysis required extensive resolution manipulation of data acquisition and plotting software.

$$V_{det}\Big|_{n+0.5} = \frac{\Delta x}{\Delta t} = \frac{L_{n+1} - L_n}{t_{n+1} - t_n} \quad (2)$$

A. Tests at Low Operating Frequencies (< 10 Hz)

Figure 7 compare CDSI, Single TPI and Dual TPI DDT performance as a function of mass flow rate. CDSI data supports previous NPS results, which showed limited success at mass flow rates higher than 0.137 kg per second. CDSI had an overall detonation success rate of 37% as opposed to 94% detonation success rate on TPI configurations. The TPI configurations allowed for tests at maximum flow rates of the current facility, 0.5 kg/s.

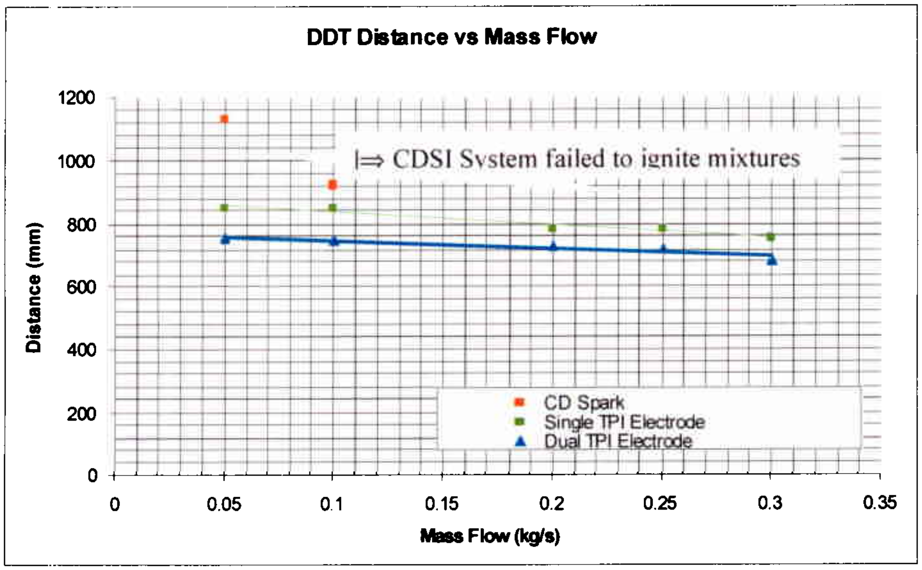

Figure 7. DDT Distance Performance vs. Mass Flow for CDSI, Single TPI and Dual TPI Configurations

In the Dual TPI configuration, an optimum time delay range between electrode discharges was determined. For the L1-L2 configuration, the optimum time delay range was from 550 to 610 μs. Performance of the L1-L3 configuration did not surpass the L1-L2 configuration, but the results were comparable to the single TPI electrode configuration.

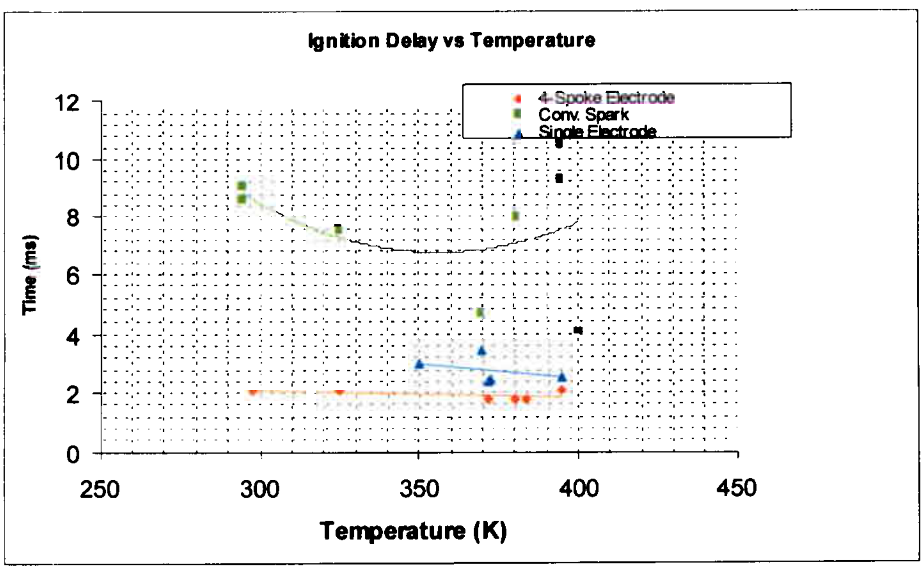

Figure 8. Determination of Ignition Time Delay vs mixture Temperature

Figure 8 shows early ignition delay time results obtained for a small variations of temperature. The TPI system with a simple and with a 4-spoke electrode consistently produced time delays less than 4 ms, meanwhile the CDSI system produced time delays between 4 and 11 ms, mostly falling around 8 ms. The tests with the 4 spoke electrode appear to not be influenced by variations in mixture temperature, where as, the results from the simple electrode tests indicate that at higher temperatures the ignition time delays slowly approach the values obtained by the 4-spoke electrode. Higher temperature tests need to be performed to corroborate this predictions.

With respect to a single versus dual-TPI electrodes, only a small difference in ignition delay was observed; and since it was found that drag losses overcome the small gains produced by adding the second electrode, it was decided that further testing of the dual TPI configuration was not needed.

B. Tests at High Operating Frequencies (10 Hz to 40 Hz)

At low operating frequencies (< 10Hz) it was very clear that the results were very similar to those found earlier [23] using single-shot tests. This indicates that at low operating frequencies it was very easy to completely isolate each PDE cycle from one another. At high operating frequencies it was expected to encounter cycle-to-cycle interactions. Up-to this time within PDE development efforts, operation at high frequencies, without the introduction of excess oxygen, has not been possible. The TPI system has allowed us to perform the following studies where CDSI systems cannot operate and thus CDSI results were not obtained.

Figure 9 shows results for ignition delay times versus mass flow rates for an ethylene/air mixture at an equivalence ratio of 1.0. This figure shows that mass flow rates do not make much of an impact on the ignition delay time as it only varied from 3.95 to 4.25 ms while the mass flow rate was increased from 0.10 to 0.40 kg/s. Meanwhile, Detonation Wave Speeds show a different trend. The speeds decrease from 1.5 km/s to just over 1.0 km/s. At 1 km/s we can safely conclude that a detonation wave was not achieved. The authors also recognize that proper instrumentation is required to properly determine the equivalence ratio within the PDE combustor as a function of axial distance. Previous work at NPS has shown that during a target equivalence ratio of 1.0, the high-speed fuel valves produce variations in equivalence ratio along the PDE combustor that equate to a fuel-rich mixtures at the head-end (with equivalence ratio values near 1.2) and fuel-lean mixtures at the aft-end (reaching an equivalence ratio near 0.9 and at times even less) [24]. This explains the lower than expected wave speeds shown below, because as shown above, the DDT distances are near 1 m for all mixtures tested, which falls at the aft-end of the PDE combustor. Therefore, due to the nonlinearities in mixture equivalence ratio, intrinsic to the high-speed fuel valves, optical spectroscopic diagnostics are required to properly determine the local equivalence ratio within the PDE combustor.

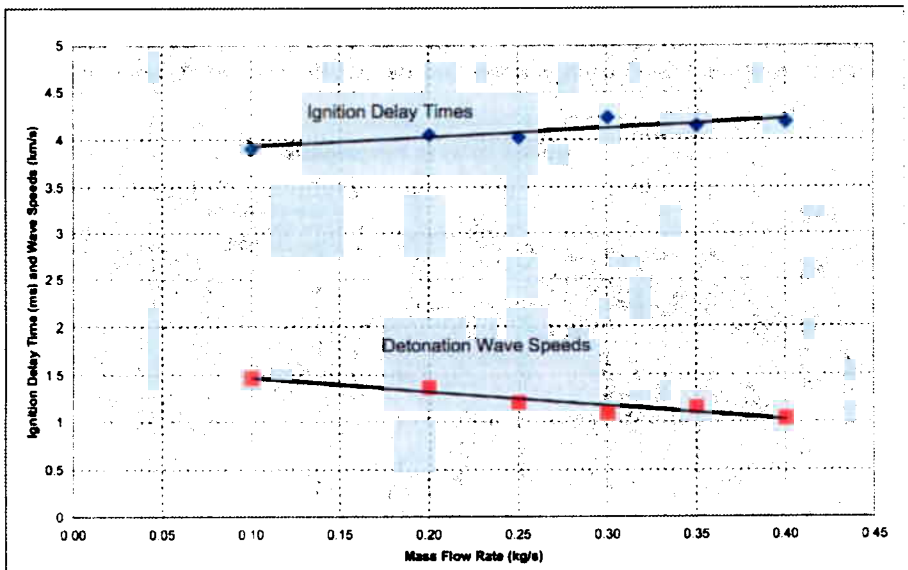

Figure 9. Ignition Delay Times and Detonation Wave Speeds vs. Mass Flow Rates for Single TPI Configurations at 40 Hz repetition rates.

Figure 10 depicts ignition delay times become lower with increasing equivalence ratio. They vary from 4 ms at an equivalence ratio of 1.0 and reduce to 2.7 ms at an equivalence ratio of 1.3. If we follow the argument presented above, a leaner mixture is produced at the aft end as a byproduct of using the high-speed fuel valves. Therefore an equivalence ratio target of 1.3 may indicate that the effective (local) equivalence ratio near the aft-end of the PDE combustor would be much closer to 1.0. Unsurprisingly, the detonation wave speeds measured increased from 1.2 km/s to slightly over 1.5 km/s.

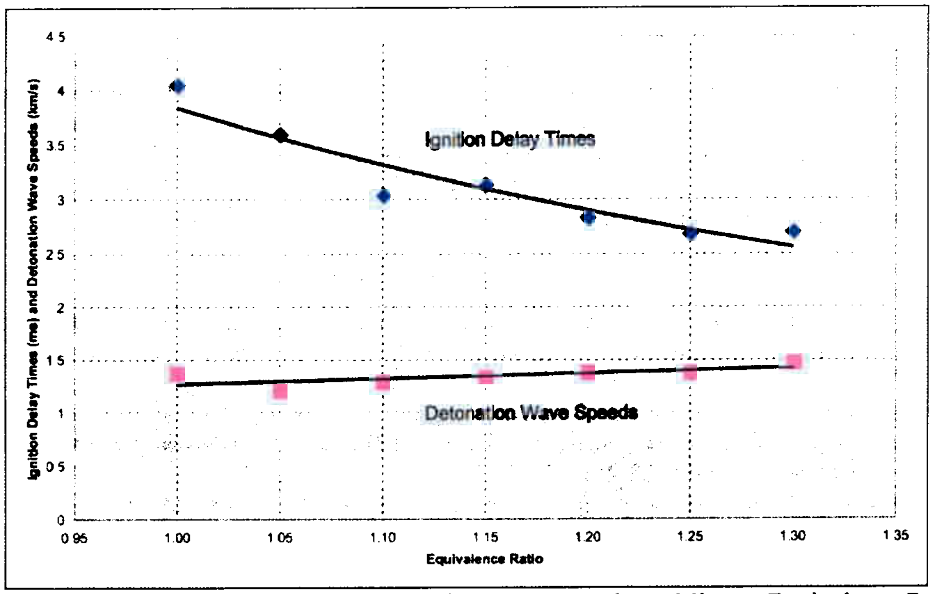

Figure 10. Ignition Delay Times and Detonation Wave Speeds vs. Mixture Equivalence Ratios for Single TPI Configurations at 40 Hz repetition rates.

The turbulence generating obstacles (the Schelkhin spirals), or lack there of, proved to be a critical factor in several test runs for both Single and Dual TPI configurations and for the CDSI configuration as well. As expected, all configurations without the Schelkhin spirals failed to initiate a detonation wave [21, 22]. Figure 11 shows the success rates for detonation initiation using the TPI system at varying mass flow rates. At 0.30 kg/s or below, 100% success rates were achieved. At 0.35kg/s flow rates only 50% success rates are achieved, and at 0.4 kg/s only 30% success rates were achieved. At this time it is not known what is the cause for such behavior, but PDE cycle-to-cycle interactions as well as the possibility of reaching a sonic point within the flow path are two of the problems that may explain this behavior. Further testing is required to fully understand the results shown in Fig. 11.

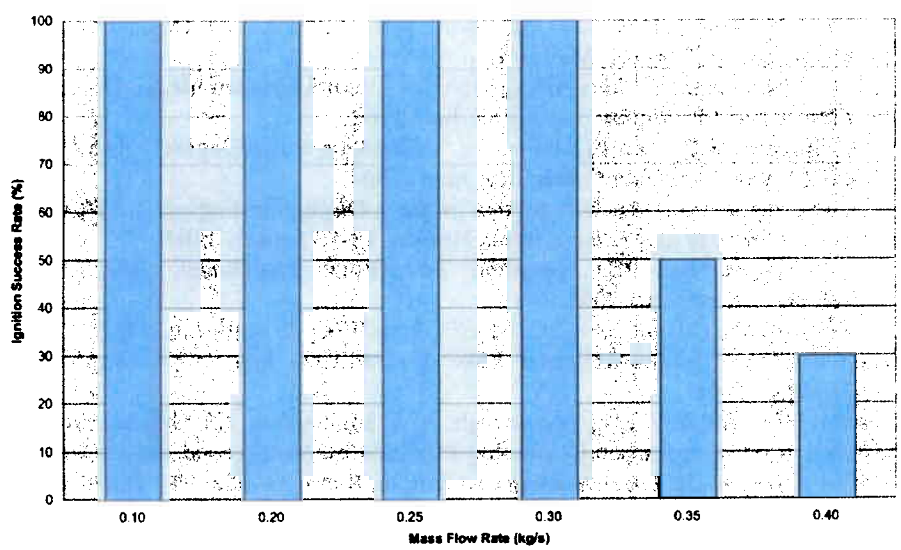

Figure 11. Detonation Ignition Success Rates of TPI System vs. Mass Flow Rates.

IV. CONCLUSIONS

Transient Plasma Ignition technology has been proven to be more effective and reliable than high-performance Capacitive Discharge Spark Ignition systems. A noteworthy improvement in DDT performance proves that TPI allows the complete removal of the auxiliary oxygen currently required in PDEs. Single TPI configurations when compared to CDSI runs, reduce DDT distance, on average, by 100 mm and DDT times are reduced by 5 ms, which is equivalent to a factor of 2.5 reduction.

When the electrodes were set at L1 and L2, the dual TPI configuration did slightly accelerate the DDT process, but with much greater drag losses. When compared to CDSI runs, the dual TPI configuration resulted in reduced DDT distances and times by 170 mm and 6 ms, respectively. The feasibility of this configuration was proven, but due to the aforementioned drag losses, further testing of the dual TPI system was not pursued.

High operating frequencies, of up-to 40 Hz, without the addition of excess oxygen were achieved using the single TPI configuration with ethylene-air mixtures at mixture ratios near stoichimetry.

V. FUTURE WORK

Further testing is already under development; near future goals include the testing at elevated temperatures and the addition of a nozzle to simulate both total temperatures and pressures encountered at supersonic cruising conditions [17].

Real-time optical spectroscopic measurements are required to properly determine the local equivalence ratio within the PDE combustor. Such instrumentation will allow to fine-tune the transient plasma ignition enabled PDE and optimize its operating parameters [24-26].

Thrust stand measurements are required to measure propulsion efficiencies as well as specific impulse performance and specific fuel consumption.

Acknowledgments

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