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Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines

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This paper reviews the testing and evaluation of transient plasma for pulse detonation engine (PDE) ignition conducted at five laboratories. It also presents data showing significant reductions in times required for detonation. Critical to achieving functional levels of thrust are increased repetition rates, thus minimal delay to detonation times are an important parameter. Experiments have been conducted at the University of Southern California and in collaboration with researchers at the Naval Postgraduate School, Wright Patterson Air Force Research Laboratory, Stanford University, Ohio State University and the University of Cincinnati. In these studies it was observed that TPI significantly reduces delay times (factor of 2 to 9) in both static and flowing systems.

I. Introduction

THIS paper reviews testing and evaluation of transient plasma for pulse detonation engine (PDE) ignition under various conditions. The aerospace community has ongoing interests in the development of propulsion technologies based on pulse detonating engines (PDEs), and work is underway to determine whether this is a feasible technology. The PDE provides impulse through fuel detonation, and its potential advantages include efficient operation at both subsonic and supersonic speeds. In theory, a PDE can efficiently operate from Mach 0 to more than Mach 4.[1, 2] In order to achieve almost continuous thrust, firing rates of 100 Hz or more are needed. Critical to achieving high repetition rates are minimal delay to detonation times. In work supported by the Office of Naval Research and the Air Force Office of Scientific Research, transient plasma ignition (TPI) has consistently

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shown substantial reductions in ignition delay time for various fuels.[3,4,5] Experiments have been conducted at the University of Southern California and in collaboration with researchers at the Naval Postgraduate School, Wright Patterson Air Force Research Laboratory, Stanford University, Ohio State University, the University of Cincinnati, and California Institute of Technology.[6] In these studies it was observed that TPI significantly reduces delay times in both static and flowing systems. Transient plasma ignition is attractive as an ignition source for PDEs because it produces reductions in ignition delay times, can reduce Deflagration to Detonation Transition (DDT) times, and has been shown to provide the capability to ignite under leaner conditions. This allows for high repetition rates, high altitude operation, and the potential for reduced NO_x emissions.[7,8] The geometry of the discharge area is such that ignition is achieved with a high degree of spatial uniformity over a large volume relative to traditional spark ignition.

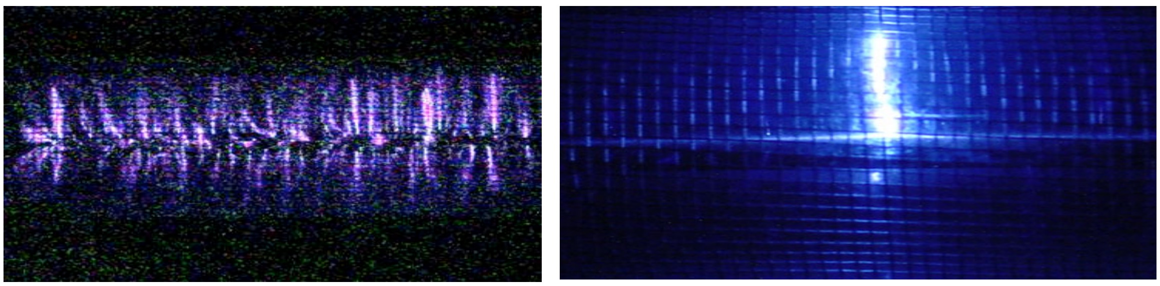

Figure 1: Transient plasma discharge (left), and spark discharge (right) to a metal mesh from a central anode. Observe the coaxial geometry allows for a voluminous array of streamers over the anode length.

The short timescale of the pulse (< 100 ns) prevents formation of an arc, and a voluminous array of streamers is used for ignition. It is possible that energetic electrons in the highly non-equilibrated electron energy distribution of the streamers cause dissociation of hydrocarbon chain molecules, producing active radicals throughout the ignition volume.[9] The generation of a large number of radicals over the discharge volume seeds chain branching and propagation reactions such that multipoint ignition rapidly occurs.

In a PDE thrust scales linearly with repetition rate (and tube volume), thus if ignition delay is reduced by a factor of two, repetition rates can be potentially doubled, and thus thrust is potentially doubled (assuming there are no other limiting factors that occur). The two major limiting factors for high repetition rate operation in a PDE are ignition delay and the gas exchange time. Through the use of transient plasma as an ignition methodology, ignition delay has been substantially reduced (factor of 2 to 9) relative to a traditional spark, making it potentially an enabling technology for multi-cycle PDE operation. The duration of the PDE's operating cycle is generally on the order of 10s of milliseconds. It is important to note that for a PDE to achieve enough thrust to be a viable technology repetition rates of 60 Hz are needed, and 100 Hz or more are desired.

II. Experimental Setup

A. TPI Generation

For the work discussed in this paper the transient plasma is generated by a line type pseudospark switched pulse generator. The pulse generator is capable of creating a 50-75 ns pulse up to 90 kV, which creates a discharge as seen in Figure 1.[10] The key element in the pulse generator is the pseudospark switch, which is a gas based cold, hollow cathode switch that is capable of switching 30 kA, with a rise time of 8 kA/ns. The pulse generator is based on the Blumlein architecture. However, instead of using transmission line, capacitors are used to make the pulse forming network. This results in a minimum pulse that is a critically dampened pulse, which will give voltage amplitudes of 64% of the charging voltage across the load. This differs from a traditional Blumlein pulse in which one obtains 100% of the charging voltage across the load. The pulse generator can be used in conjunction with a high voltage DC supply or a rapid charger for high repetition rate operation, typically for ignition application operation around 100 Hz. Figure 2 depicts the pseudospark pulse generator.

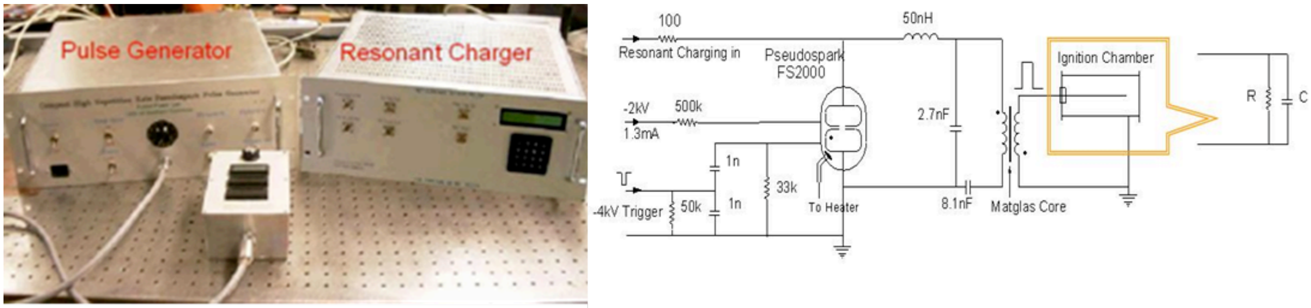

Figure 2: Pseudospark based pulse generator schematic.

The voltage and current traces for the transient plasma and a spark discharge are markedly different. In the transient plasma case, the voltage and current overlap, which implies that real power is being generated. However, in the spark discharge case the voltage will generally increase with no current, and then drop suddenly to zero with an increase in current as an arc is generated. This lack of overlap implies that in the spark discharge most of the energy is passing through the reactor and will be dissipated in the circuit, and not dropped across the load (typically less than 5% of the energy is deposited in the medium).

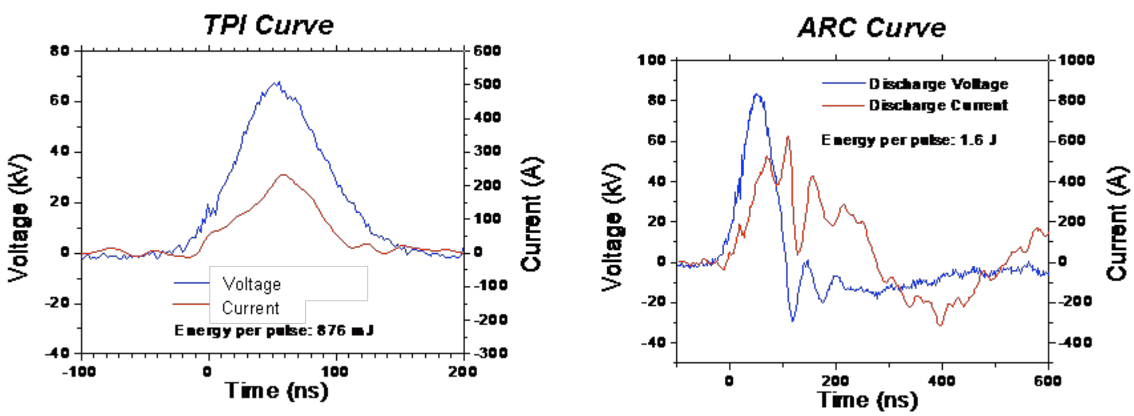

Figure 3: Transient Plasma (left) and transient plasma that coverts to an arc (right).

B. Experimental Setup

The interface between the TPI system and the PDE is largely the same for the various experiments (Figure 4). In general a HV charging source, in the form of a HV DC supply or a resonant charger, is used to charge the pseudospark switched pulse generator. Generally the pressure is measured with high speed pressure transducers, and wave speed is measured with multiple ion probes running the length of the tube.

A typical electrode is an 8-32" threaded rod, which is threaded for field enhancement to assist in streamer development. It is about 5" in length and acts as the anode running coaxially in the center of the tube at the engine head. The electrode seen in Figure 5 was developed for the Wright Patterson tests that follow, and is typical in structure of the electrodes used. The ceramic is MACOR, which is rated at about 1000 Volts/mil, and has a CTE relatively close to steel. The outer ground cylinder is steel, and acts as the return path for the discharge current. The electrode can be installed or removed from the system without the removal of the PDE tube (improvement over previous TPI electrode designs). Additionally the threaded rod's length can be adjusted to control the volume of the discharge. In previous designs the electrode had to be installed prior to mounting the tube, and thus any changes to its configuration or needed repair were difficult to achieve. It is also important to observe that it is a purely coaxial design. This was done largely to keep the noise down to a manageable level. EMI becomes a very large problem for nearby devices if unshielded connections are used.

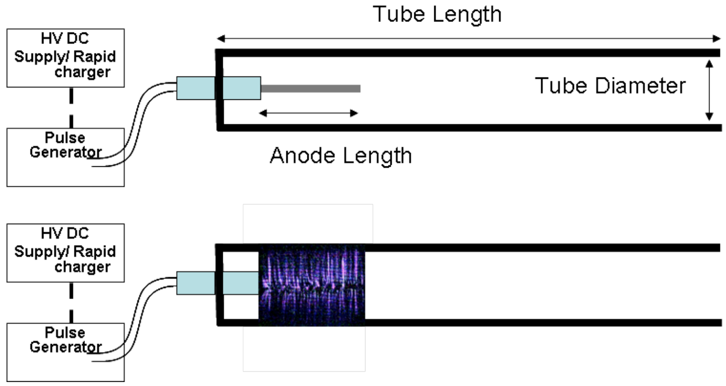

Figure 4: Top image is general configuration of TPI interface. Bottom illustrates streamer formation.

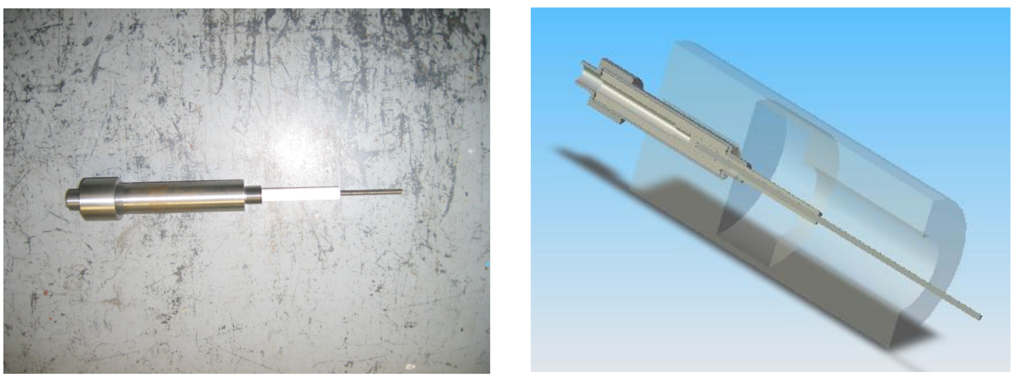

Figure 5: HV TPI electrode developed to feed through the 14mm interface used in the WP PDE.

The NPS experiment called for a 3" ID tube, with an electrode length of ~ 3 to 6 inches. The PDE is a valve less system that does not modulate the airflow through the engine. Its diameter is such that it allows for a minimum of 2 detonation cells sizes for a variety of fuels. The overall length of the engine was 1.13 m, with a Schelkhin spiral length of 0.914m. Repetition rates up to 40 Hz were tested under varying mass flow rates. For a detailed examination of the setup outlining the NPS experimental setup see the paper presented in reference 12.

The Wright Patterson experiment used a PDE consisting of a quad engine head and four detonation tubes.[11] The tubes were 2.067 inches in inner diameter, and were 73 inches long. Only two of the four detonation tubes were used for the Aviation gasoline (AVGAS) testing, and the one tube was used for the Hydrogen testing. In the multiple tube case, one tube was run with a sparkplug, and the other tube held the transient plasma electrode and was fired 180 degrees out of phase. This was done to maintain balance and reduce excess vibration in the system. The AVGAS was heated to 200° F upstream of the inlet to vaporize the fuel. A pressure transducer was located at the head of the tube, and there were seven ion probes spaced along the tube. Shchelkin-like spirals were used in both the AVGAS-air and the Hydrogen-air mixtures to ensure detonation. The transient plasma was tested at 10 Hz, and was charged with a 30 kV Glassman HV DC supply.

The Stanford experiment used a 1.5" ID tube with an electrode length of ~ 6 inches. Five pressure probes and seven ion probes were used. Additionally, a PDA 55 Silicon photodetector used in conjunction with a 308nm bandpass filter was used to monitor OH* emission.

III. Results and Discussion

A. Naval Postgraduate School

In work performed in collaboration with NPS we demonstrated at high flow rates where spark-initiated flames are normally extinguished, the transient plasma is able to ignite and effectively create a detonation wave.[12] Significant reduction (factor of 4) in ignition delay was shown for C_2H_4 – air mixtures. Additionally the TPI ignition delay seemed relatively invariant to temperature and was at comparable energy levels with the conventional sparkplug baseline (Figure 6). Tests at NPS prior to the introduction of transient plasma as an ignition source were limited to low frequency operation, unless extra oxygen was introduced into the system. While extra oxygen in the lab may be okay, on an airborne platform the extra oxygen adds complexity, cost, weight, and increases the hazard levels to the overall system. Additionally, this experiment acted as a preliminary study showing that the mass flow rate has little effect on the ignition delay. However, as the mass flow rate increases, a decrease in the detonation wave speed is observed. The ignition delay varied from 3.95 ms to 4.25 ms as the mass flow rate varied from 0.1 to 0.4 kg/sec. As the ignition delay and mass flow rate increased, the detonation wave speed decreased from 1.5 km/sec to just over 1 km/sec. The latter case at 1 km/sec does not achieve a detonation wave. Moreover, this experiment tested possible multiple electrode configurations to facilitate pulsing the mixture several times as it transitioned down the tube. It was found that multiple pulses did in fact further reduce ignition delay, however, the drag losses introduced by the secondary electrode made this approach practically unfeasible. More recently, work has been performed at NPS using the TPI igniter in search of optimal spiral length for DDT reduction.[13] This is a preface to work that is currently being done at NPS to test a new staged PDE engine design where TPI is the ignition source.

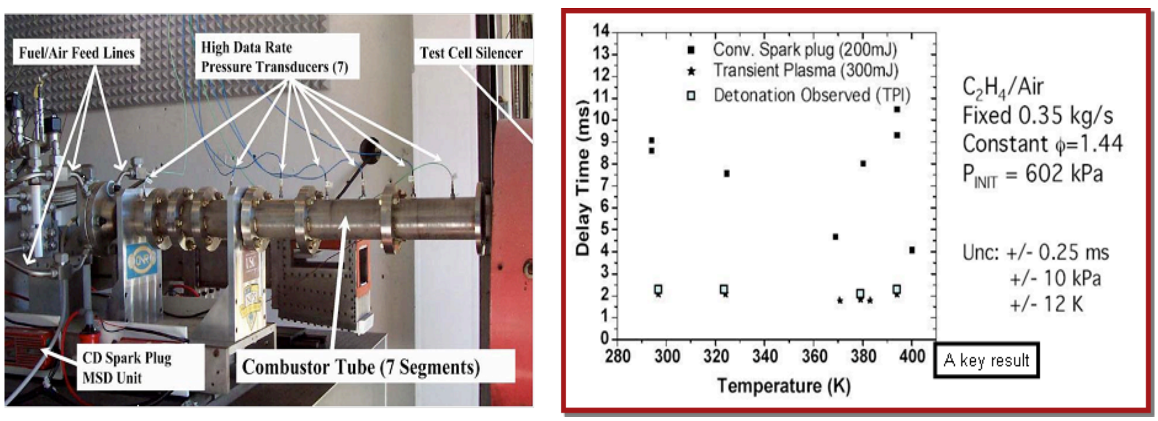

Figure 6: The left figure shows a valve less PDE setup at the Naval Postgraduate School. This type of architecture requires a booster, and its anticipated applications are missiles or rockets. The right figure shows a factor of 4 reduction in ignition delay for ethylene-air.

B. Wright Patterson Test

Tests conducted at Wright Patterson Air Force Base were performed, where TPI was first used on a valved PDE. For these first tests, H_2-air and aviation gasoline (AVGAS)-air mixtures were used. Shchelkin-like spirals were used for the H_2 as well as for the AVGAS mixtures in order to promote the DDT process. In hydrocarbon-air mixtures the reduction in ignition delay is of primary importance due to the low residence times experienced in vehicles traveling at high speeds (low hypersonic speeds) where ignition delay times can be orders of magnitude larger than the flow residence time. The ignition delay results for AVGAS are depicted in Figure 7. A reduction in the ignition delay by a factor of 2 was obtained here. The lean burn capabilities of the transient plasma ignition were also demonstrated. The transient plasma was able to reliably ignite AVGAS – air mixtures at equivalence ratios of nearly 0.65, whereas the baseline's lower limit was 0.71. The widening of the range of operation into the lean side of the curve is advantageous for high altitude engine operation. Also the lean operation allows for a more economical use of fuel when cruising, as well as reduces NOx emissions. The reduced performance of the 66 kV pulse relative to the 59 kV pulse is likely resultant to small energy losses due to inadequate insulation between the electrode and the engine head. This is as compared to higher pulse voltages in which small parasitic arcing may have occurred from the HV cable/electrode interface to the engine head.

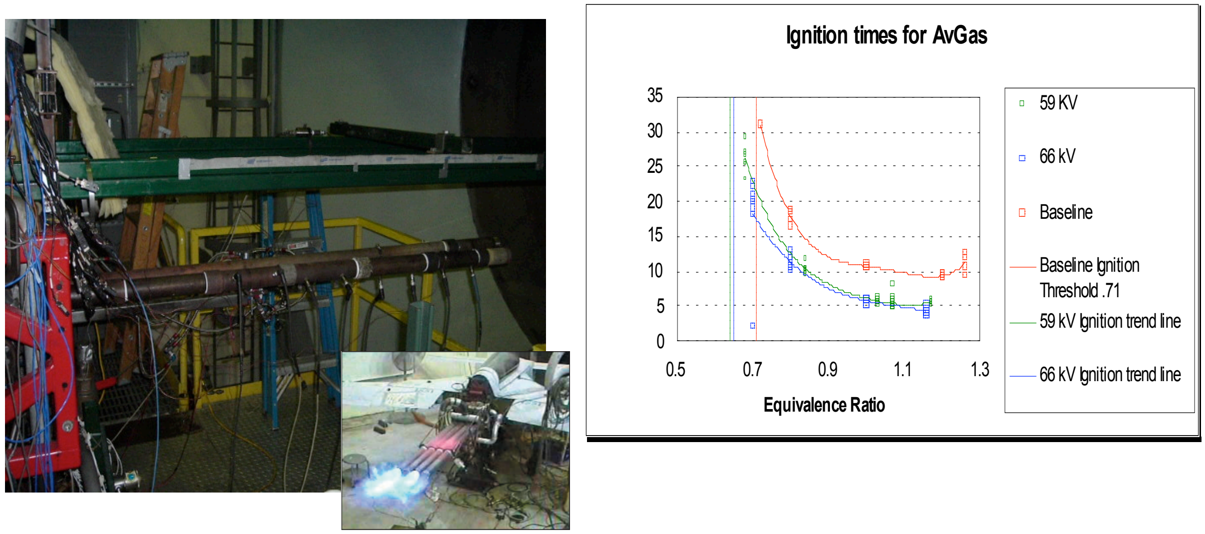

Figure 7: The left figure shows a valved PDE at Wright Patterson Air Force Base. The valved architecture would be used for an aircraft and would need no booster. The right figure shows a factor of 2 reduction in ignition delay for aviation gasoline.

For Hydrogen-air mixtures the reduction in ignition delay is important, primarily at high hypersonic cruising speeds where the flow residence time is very short. Hydrogen – air mixtures were also tested during these first experiments, primarily because they are relatively easy to detonate. Figure 8 depicts this ignition delay and the DDT times under these conditions. Observe that TPI was able to reduce the ignition delay time for H_2 – air mixtures almost by a factor of 2. The figure also depicts the DDT times for H_2 – air mixtures, which seemed to be on the order of the baseline with little or no improvement. The DDT times for AVGAS were similar in that TPI seemed to have little effect. That having been said, it should be noted that the error spread for the DDT times for H_2 and AVGAS – air mixtures were quite large, and efforts are currently underway to try to further process the data and reduce the error. To date there has not been a lot of work done on TPI's effects on DDT. Looking at the data taken at WP over the past two years, it suggests that besides ignition delay times, DDT is primarily controlled by fluid dynamics, and may be independent of ignition methodology.

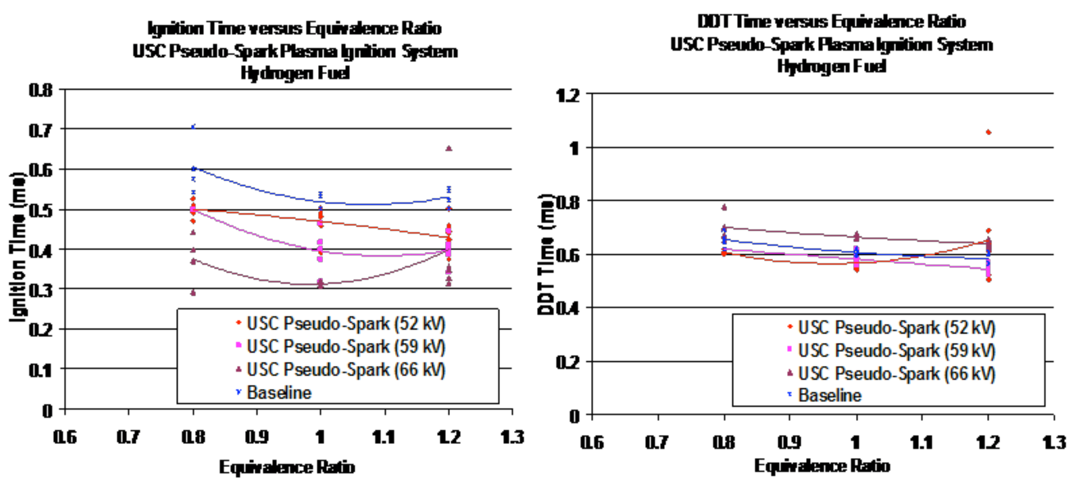

Figure 8: Ignition delay and DDT time for H_2-air mixtures.

C. Stanford University

An example of TPI integration with a PDE is shown in Figure 9. TPI ignition of $C_2H_4 - O_2$ mixtures resulted in ignition delay reductions by nearly one order of magnitude (factor of 9). Of further interest are the OH emission measurements. There is a large difference in the amount and form of the emission signal shown in figure 10. This is a preliminary result and needs to be confirmed, however, it does possibly suggest that TPI is a new ignition process.

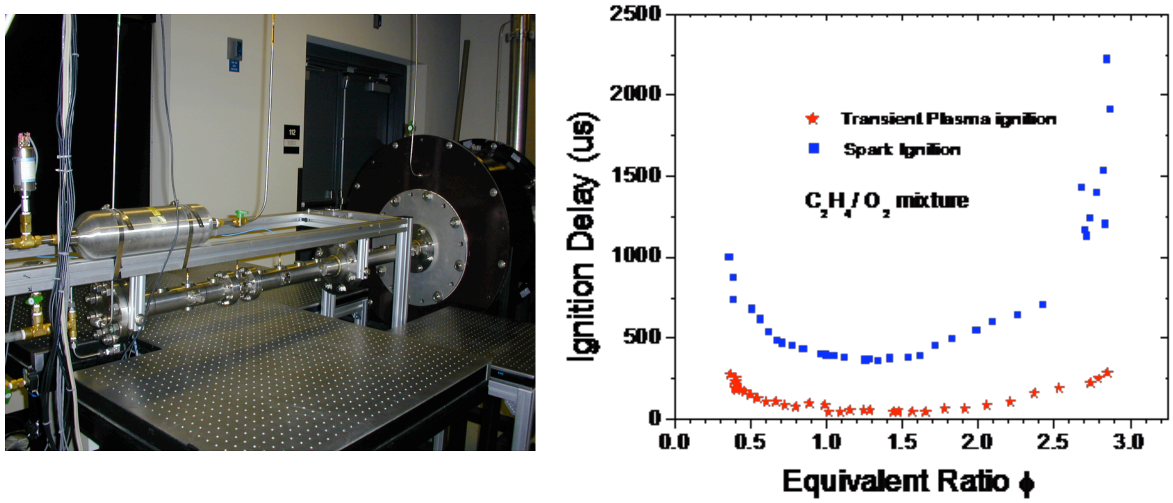

Figure 9: The left figure shows a PDE setup at Stanford University. The right figure shows a factor of 9 reduction in ignition delay for Hydrogen-Oxygen mixtures.

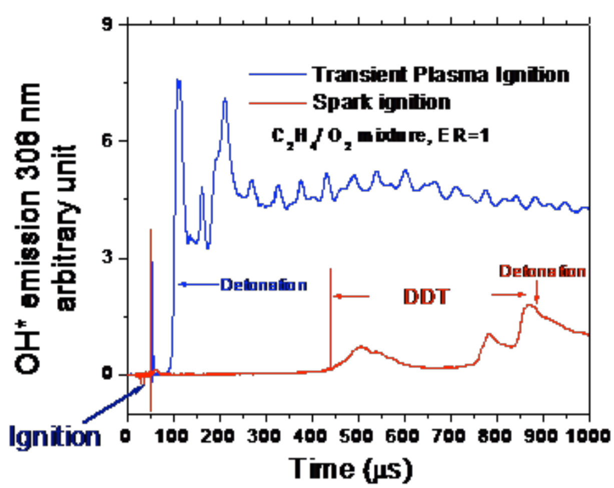

Figure 10: OH emission on Stanford PDE.

D. Summary

Table 1 depicts some of the ignition delay data taken at Stanford University, the Naval Postgraduate School, and Wright Patterson Air Force Base. Thrust scales linearly with repetition rate, and it is apparent from the results, tested under a variety of conditions, that transient plasma is potentially an enabling technology for high repetition rate operations. Under varying test conditions delay to detonation reductions ranging from factors of 2 to 9 were found. Generally hydrocarbon-air mixtures were tested, however, hydrogen-air and hydrogen-oxygen mixtures were also tested. This table indicates the delivered energy per pulse. While in general TPI delivers mores energy than a conventional sparkplug, it can deliver pulses of comparable energy and still provide significant reductions in ignition delay.[14]

Table 1: Transient plasma ignition of PDE results[15]

	Lab	Fuel	Oxidizer	Ignition Delay (msec)	DDT (ms)	Energy Delivered (J)
TPI	Stanford	C_2H_4	O_2	0.05	0.05	1.16
Spark	Stanford	C_2H_4	O_2	0.5	0.45	.075
TPI	NPS	C_2H_4	Air	2		0.3
Spark	NPS	C_2H_4	Air	8		0.2
TPI	WPAFB	AVGAS	Air	6	2.25	0.67
Spark	WPAFB	AVGAS	Air	10	1.7	.115
TPI	WPAFB	AVGAS	Air	5	2.5	0.87
Spark	WPAFB	AVGAS	Air	10	1.7	.115
TPI	WPAFB	H_2	Air	0.4	0.57	0.67
Spark	WPAFB	H_2	Air	0.51	0.61	.115
TPI	WPAFB	H_2	Air	0.3	0.67	0.87
Spark	WPAFB	H_2	Air	0.51	0.61	.115

Transient plasma ignition is definitely a viable technology and potentially an enabling technology for PDEs. This is still a relatively new area of research, and there is still a lot that needs to be explained, such as the physical processes behind transient plasma ignition. Transient plasma as an ignition source has a significant impact on the ignition delay times of the system, allowing for higher frequencies of operation. This increase in frequency directly correlates with thrust, and thus solves one of the biggest obstacles in producing a practical PDE to date at potentially comparable energy cost to the traditional spark.

IV. Conclusions

Transient plasma ignition is on the cutting edge of ignition methodologies for combustion engines. The PDE community in particular is interested in this technology for several reasons: 1) the capability to ignite in a manner that achieves detonation in hydrocarbon-air mixtures (without a previously required oxygen supplement); 2) the extension of the lower flammability limit of mixture and 3) the capability to reduce ignition delay times by factors of 2 – 9 offers comparable potential for increases in repetition rates. For these reasons transient plasma has the potential to overcome the traditional capacitive and inductive spark discharge, and laser discharge ignition techniques.

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