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***Abstract*—The use of a compact solid-state pulse generator and compact igniters for transient plasma ignition in a pulse detonation engine (PDE) is reported and compared with previous results using a pseudospark pulse generator and threaded rod electrode. Transient plasma is attractive as a technology for the ignition of PDEs and other engine applications because it results in reductions in ignition delay and has been shown to ignite leaner mixtures which allows for lower specific fuel consumption, high-repetition rates, high-altitude operation, and reduced NOx emissions. It has been applied effectively to the ignition of PDEs as well as internal combustion engines. Nonequilibrium transient plasma discharges are produced by applying high-voltage nanosecond pulses that generate streamers, which generate radicals and other electronically excited species over a volume. The pulse generator used is in this experiment is capable of delivering 180 mJ into a 200-Ω load, in the form of a 60-kV 12-ns pulse. Combined with transient plasma igniters comparable with traditional spark plugs, the system was successfully tested in a PDE, resulting in similar ignition delays to those previously reported while using a smaller electrode geometry and delivering an order of magnitude less energy.**

***Index Terms*—Combustion, deflagration-to-detonation transition (DDT), pseudospark, pulse detonation engine (PDE), streamers, transient plasma.**

I. Introduction

In improving pulsed-power-system performance for transient plasma ignition (TPI), it is critical to increase reliability and decrease system volume and weight since combustion systems typically require components that can operate in high-temperature and high-vibration environments where size and weight place further constraints on the system [1]. To that end, a new pulse generator and electrode system was designed for use in an internal combustion engine (ICE) and/or a pulse detonation engine (PDE) and was tested in the PDE at the Naval Postgraduate School (NPS).

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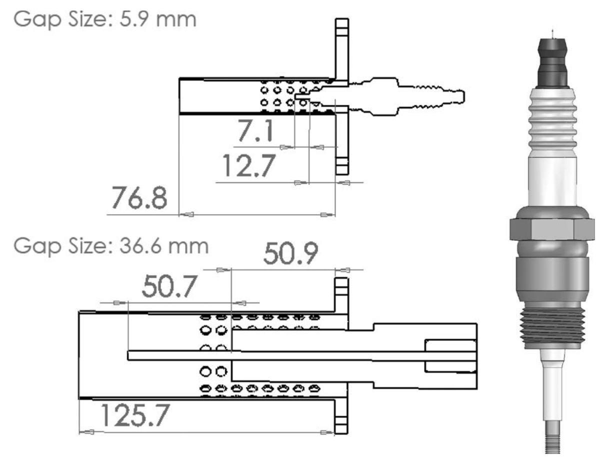

Fig. 1. Section view of (top left) the transient plasma igniter and grounded screen for the 12-ns TPI system compared with (bottom left) the threaded rod and grounded screen for the 85-ns TPI system. Dimensions are in millimeters. An enlarged view of the transient plasma igniter is shown on the right.

In pulse generator design, the switch is one of the most important considerations. Solid-state switches are attractive for ignition applications because they eliminate the overhead (e.g., heating) associated with a gas switch, reduce size and weight, and increase reliability. A drawback of solid-state switches is the lower voltage and current ratings of the switches themselves, which place requirements on the rest of the system to compensate for those limitations. A compact 12-ns pulse generator using a silicon-controlled rectifier (SCR) as a switch was designed and built to decrease the system size and weight and to decrease the pulsewidth compared with a 20-ns insulated-gate bipolar transistor (IGBT)-based pulse generator previously presented [2]. The advantage of decreasing the pulsewidth and therefore allowing an increase in the applied voltage while avoiding an arc was shown in an ICE experiment in collaboration with the Nissan Research Center [3]. In that experiment, because of the short gap (6.4 mm), using a 20-ns pulse compared with an 85-ns pulse allowed a significant increase in the reduced electric field E/n (E is the applied electric field, and n is the gas density) without causing spark breakdown, which increased the number of high-energy electrons capable of dissociation and ionization and resulted in an additional 20% increase in peak pressure in the engine cylinder.

The electrode previously used (85-ns TPI system) in the PDE at NPS (Fig. 1) consisted of a stainless steel rod, threaded for field enhancement and insulated by a ceramic (Macor). A steel coaxial cylinder was grounded and acted as the return path for the discharge current and created a large discharge gap

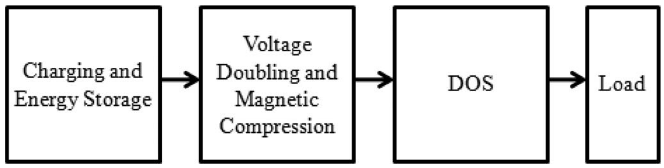

Fig. 2. Train diagram for a 60-kV 12-ns compact pulse generator.

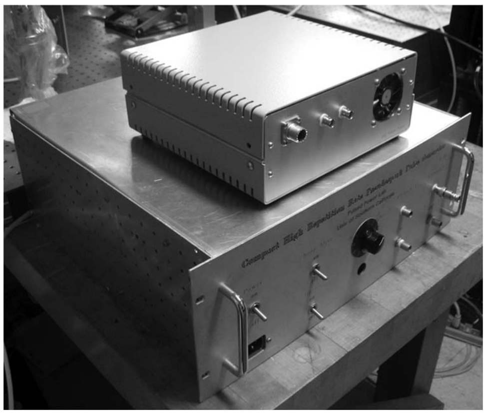

Fig. 3. (Bottom) 90-kV 85-ns pseudospark pulse generator. (Top) 60-kV 12-ns solid-state pulse generator.

(36.6 mm). Previous Macor insulators have failed due to mechanical vibration and were not easily replaced; therefore, a smaller, more robust, and easily replaceable solution was required. The igniters used in this experiment (12-ns TPI system) are similar in size, weight, and design to a commercial spark plug and are combined with a coaxial stainless steel grounding screen (Fig. 1). The gap size is small (5.9 mm) and requires a short pulse to hold off spark breakdown.

II. Pulse Generator

The pulse generator used in this experiment is capable of delivering a 60-kV 12-ns (FWHM) pulse (180 mJ) into a 200-Ω load. The amplitude is scalable while maintaining the same pulsewidth down to an output voltage of 20 kV. The rise time of the pulse is around 5 ns. The pulse generator (Fig. 2) consists of three stages: 1) a rapid charging and energy storage stage, which allows a repetition rate up to 1 kHz; 2) a voltage doubling and magnetic compression stage; and 3) a diode-opening-switch stage.

An inexpensive SCR replaced the relatively expensive IGBT as the switch, which subsequently required that the charging voltage be reduced from 1 kV to 500 V. The size of the 12-ns pulse generator was reduced to a unit with a volume less than 6500 cm^3 compared with a unit with a volume of 28 000 cm^3 for the 85-ns pulse generator (Fig. 3).

The typical output voltage and current waveforms are shown in Fig. 4. Current and voltage were measured using a fast Pearson Electronics current transformer (Model 6223) and a custom 1 : 1000 high-voltage divider and recorded using a 1-GHz Tektronix digital oscilloscope (DPO 4104). For this experiment, the output voltage was reduced to 50 kV, due to the small gap of the igniters. The energy delivered was around 80 mJ per pulse.

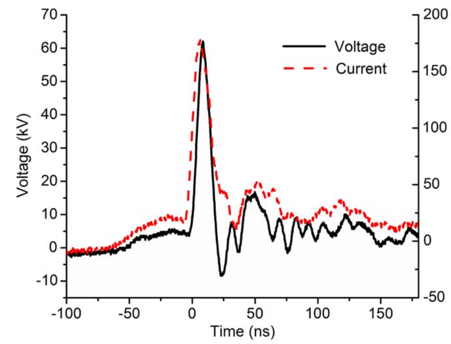

Fig. 4. Output voltage and current of the 60-kV 12-ns pulse generator. The load is 200 Ω.

III. Experimental Setup

The experiments were performed at the Rocket Propulsion Laboratory at NPS. A schematic of the experimental setup is shown in Fig. 5, which shows the location and configuration of the TPI system within the PDE. The electrode system used with the 12-ns solid-state pulse generator was similar in size to a commercial spark plug, but 20 mm of the grounding shell was removed, eliminating the grounding arm and leaving exposed 18.6 mm of the insulator and a 2.6-mm-long smooth anode. A 4.5-mm-long threaded rod (2.1-mm diameter) was attached to the end of anode to increase the length. It was threaded for electric field enhancement. A perforated ignition shield was used as the cathode. Initial tests were performed with a porosity of 25% on the ignition shield. This provided a lower velocity region inside the discharge volume and enabled sufficient development of a flame front in the tested fuel–air mixtures, which subsequently produced successful deflagration-to-detonation transitions (DDTs) in the main detonation combustor after passing over turbulence-generating devices.

The tests performed at NPS investigated the variation of ignition delay times as a function of fuel–air equivalence ratios in a PDE configured to simulate Mach 2.5 cruise conditions at an altitude of 40 000 ft. At this velocity, stagnation temperatures near 500 K are required. The NPS configuration is a direct-connect test rig; therefore, air heating is required. The airflow was heated using a hydrogen-fueled vitiator system, which utilizes oxygen to rebalance the oxygen content of the heated air up to the standard mole fraction of 21%. At a short distance (less than 1 m) downstream of the vitiator, a stagnation plenum is used to feed the four mixing arms in which fuel is injected and allowed to mix with the heated airflow. Either liquid or gaseous fuels or a combination of these can be injected. In these investigations, gaseous ethylene (C_2H_4) was used. The ethylene–air mixtures were then introduced into the PDE as shown in Fig. 5, where a portion of it passes through the porous screen and fills the TPI discharge volume with much lower velocities than the surrounding flow. It is the lower velocities that enable a fully developed flame front to evolve, and it evolves rapidly in conjunction with the volumetric discharge of the TPI system. The inlet Reynolds number was Re $\sim$200 000, and the temperature of the fuel–air mixture at the entrance to the PDE was 490 K.

Once evolved, the flame front must still go through DDT within the main detonation combustor, where Shchelkin-type obstacles strategically placed along the main detonation

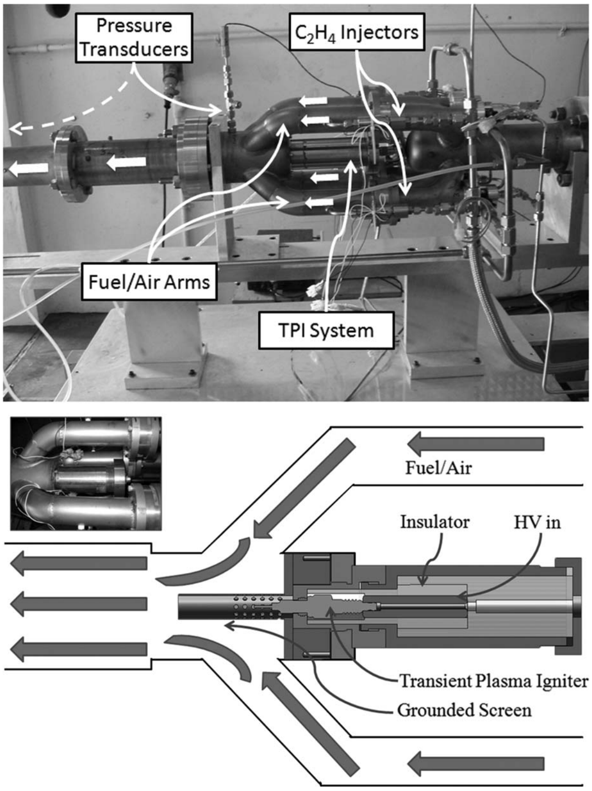

Fig. 5. (Above) PDE at NPS with the compact igniters installed. High-speed dynamic pressure transducers were used to measure the pressure rise from a combustion event at different locations and determine ignition delay time. A section view of the TPI PDE system is shown below. The length of the grounded screen beyond the porous section reduces recirculation zones as the fuel–air mixture flows from the arms into the main detonation combustor.

combustor enable DDT to occur within 1 m, in a 75-mm-diameter combustor. After detonation, a 2-ms or longer purge process is allowed prior to the start of the next cycle, in order to prevent the hot products from preigniting fresh ethylene–air mixtures. Although the flow rates can be varied from 0.15 kg/s to greater than 0.5 kg/s, all tests reported herein were performed at 0.35 kg/s, which allowed PDE operating frequencies of 40 Hz without any adverse behavior.

Instrumentation was composed of high-speed Kistler Type 603B1 dynamic pressure transducers with matching charge amplifiers. These respond within 2 μs, and their signals were digitized at a 1-MHz sampling rate using 14-b National Instruments Analog-Input DAQ boards mounted on a PXI system. In addition, laser-based absorption spectroscopy was used to measure the ethylene content in the mixture, which allowed us to calibrate set equivalence ratios. A CW HeNe laser tuned to the infrared 3.39-μm wavelength was used with a PbSe-based diode detector. As the ethylene–air mixture flowed through the engine, the laser beam intensity decreases, and this intensity decrease is proportional to the concentration of ethylene in the mixture from Beer's Law. These measurements were performed only during nonignition tests as blast waves in the test cell formed from exiting detonation waves could damage the HeNe. Previous investigations [4]–[6] in collaboration with Stanford University have demonstrated fuel concentration (among others, such as temperature, water concentration, etc.) measurements during hot tests using fiber launched tunable diode lasers. Lastly, type-K thermocouples were used throughout to determine airflow inlet temperatures and to control vitiator operating temperatures.

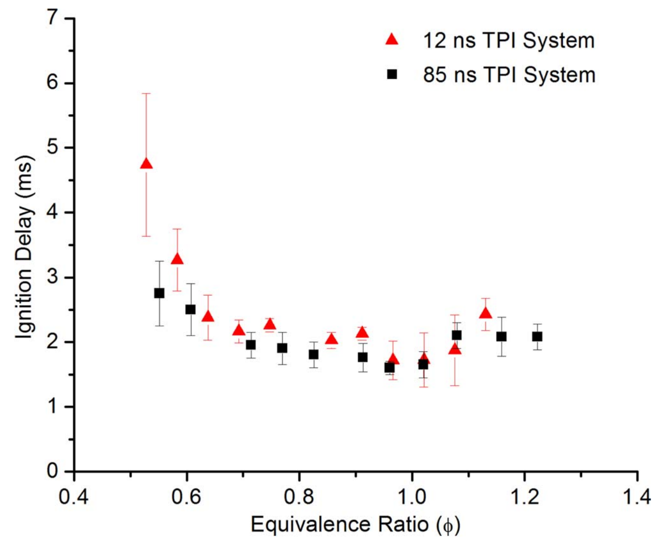

Fig. 6. Results of ignition delay in a PDE using a 12-ns TPI system (80 mJ) and an 85-ns TPI system (800 mJ).

IV. Results

The results presented are ignition delays for a varying equivalence ratio and a fixed mass flow rate of 0.35 kg/s. Two TPI systems were compared, one with an 85-ns pseudospark pulse generator and threaded anode which discharges a pulse of 800 mJ (85-ns TPI system) and the other with a 12-ns solid-state pulse generator and transient plasma igniter which discharges a pulse of 80 mJ (12-ns TPI system). The results are shown in Fig. 6. The error bars represent the standard deviation of a minimum of ten data points (with usually around 40 data points) for each equivalence ratio tested.

Both TPI systems produced similar ignition delay times near stoichiometric conditions—despite the large differences in the energy delivered and discharge volume. The 12-ns TPI system produced slightly longer average ignition delay times than the 85-ns TPI system when the mixtures were far away from stoichiometric conditions, and the difference in average ignition delays were most dramatic at very lean conditions $(\phi < 0.6)$.

Both TPI systems were able to produce successful DDTs in the main combustor. In comparison, a traditional spark-plug ignition system will not produce DDTs in this setup without additional oxygen.

V. Discussion

Ignition delay is defined here as the time from the ignition pulse to a pressure rise due to heat release [7]. Pressure transducers were located on the main detonation combustor at three locations. Location 1 was directly at the TPI discharge location, which was used to measure pressure rise from the combustion event—this was used to determine ignition delay times. The response time of the pressure transducer (2 μs) was much faster than the ignition delay times (in milliseconds). The ignition delay time was taken between the rise of the high-voltage discharge event to the time at which the high-speed pressure transducer at Location 1 registered a 1-bar pressure increase. This criteria possesses a local dp/dt value that exceeds that of

[7], thus making the ignition delay definition for the setup used in this experiment more conservative. It is difficult to compare the two rigs since the PDE in the cited work is valved, while the PDE used in this experiment has both forward and aft venting, thus making the pressure rise more difficult to achieve and reinforcing the statement that our definition is more conservative. MATLAB was used to analyze the high-frequency transducer signals and TPI discharge signals recorded in LabView.

Pressure transducer Locations 2 and 3 were set near the detonation combustor exit and were placed 100 mm apart from each other in order to measure detonation wave pressures and times of arrival so that detonation velocities could be verified. This served two purposes: indication of a successful DDT and quantification of detonation velocities for the given equivalence ratios. However, the latter is more difficult to analyze because under- and overdriven detonation states occur near detonation transition location, which for equivalence ratios away from 1.0, occurred within the 100-mm spacing between transducers. Therefore, detonation velocities versus equivalence ratios are not reported herein. At lean and rich equivalence ratios, a longer tube would be required to obtain steady-state detonation velocities.

Since the geometries of the two ignition systems used in this experiment were different, it is relevant to address the possible influence of hydrodynamic characteristics on the ignition delay time measured values. Although the shrouded volume around the electrode was larger in the 85-ns TPI system and likely resulted in a greater volume of excited reactants than in the 12-ns TPI system, the convection of the flow over such time difference of approximately 60 ns would only correspond to a spatial variation of tens of micrometers. The improvements in the ignition delay times for the rich and lean conditions were more likely due to the increased size/amount of the initial flame kernels for the 85-ns TPI system.

When comparing the measured ignition delay times between the two TPI systems, it is important to consider the difference in total energy deposited ($\sim$800 and $\sim$80 mJ for the 85- and 12-ns TPI systems, respectively), as well as the differences in the discharge volume and the reduced electric field. The discharge volume of each system was calculated using the length of the anode and the diameter of the anode and grounded screen. Streamers were present through this volume. The 85-ns TPI system had a discharge volume of 58.4 cm^3, and the 12-ns TPI system had a discharge volume of 0.3 cm^3. It is therefore interesting to note that there were very small differences in ignition delay times between both systems at near stoichiometric conditions (ϕ near 1.0).

While the discharge volume with the 12-ns TPI system was about 200 times less, the energy density delivered was about 20 times more. The energy density deposited in the 85-ns TPI system was $\sim$15 mJ/cm^3 while the energy density deposited in the 12-ns TPI system was $\sim$270 mJ/cm^3. The increased maximum electric field for the 12-ns TPI system (approximately 250 kV/cm compared with 150 kV/cm) resulted in an increase in the reduced electric field E/n (estimated 1100 Td compared with 650 Td), which increases the number of energetic electrons capable of disassociating hydrocarbon molecules, producing more active free radicals in the ignition volume. These approximations do not take into account the voltage fall across the plasma sheaths, and the anode was assumed to be smooth. The experiments described used threaded anodes which further enhanced the electric field near the anode.

It has been reported [8] that there is a threshold dependence of ignition delay times on the reduced electric field and that an increase in E/n beyond $\sim$400 Td will not result in any further decrease in ignition delay. While ignition delays were similar for the two systems at stoichiometric conditions, the 12-ns TPI system produced longer ignition delays in very lean conditions. Therefore, when considering the differences in ignition delay using the two systems in lean mixtures, the effective area of the igniters (the length of the anodes) must also be considered. Previous study [9] has shown that ignition occurs near the anode, despite the volumetric distribution of the streamers. The electric field is the highest near the anode, and therefore, the highest densities of radicals are found there. In the geometry used in this experiment, the anode was seven times shorter (7.1 mm compared with 50.7 mm) than the previous ignition system, resulting in fewer ignition kernels and contributing to the slower ignition delay times further away from stoichiometric conditions. The ethylene–air mixtures become less sensitive (less energetic) when the equivalence ratio is far away from 1.0, even more so at lean conditions; thus, the differences in ignition delay times become significant, as expected from conventional flame propagation theory [10].

VI. Conclusion

Transient plasma generated by short high-voltage pulses has consistently shown reductions in ignition delay times and broader lean flammability capability relative to traditional spark ignition. A new 12-ns compact solid-state pulse generator for ignition applications was tested using ignition geometry comparable with a spark plug. This system was compared with the 85-ns pseudospark pulse generator and threaded-rod-electrode configuration in a PDE. The ignition delay times achieved using the solid-state pulse generator and small igniter were comparable with those using the pseudospark pulse generator and threaded rod throughout, except at very lean conditions ($\phi < 0.6$). The pulse generator is attractive for mobile applications because of its small size, simple operation, and reliability.

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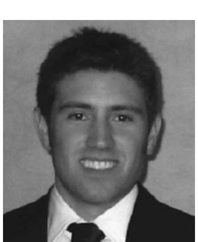

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