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Fei Wang, *Member, IEEE*, J. B. Liu, J. Sinibaldi, C. Brophy, A. Kuthi, C. Jiang, P. Ronney, and
Martin A. Gundersen, *Fellow, IEEE*

***Abstract*—Transient plasmas that exist during the formative phase of a pulse-ignited atmospheric pressure discharge were studied for application to ignition of quiescent and flowing fuel-air mixtures. Quiescent methane–air mixture ignition was studied as a function of equivalence ratio, and flowing ethane–air mixture was studied in a pulse detonation engine (PDE). The transient plasma was primarily comprised of streamers, which exist during approximately 50 ns prior to the formation of an equilibrated electron energy distribution. Results of significant reduction in delay to ignition and ignition pressure rise time were obtained with energy costs roughly comparable to traditional spark ignition methods (100–800 mJ). Reduction in delay to ignition by factors of typically 3 in quiescent mixes to >4 in a flowing PDE (0.35 kg/s), and other enhancements in performance were obtained. These results, along with a discussion of a pseudospark-based pulse generator that was developed for these applications, will be presented.**

***Index Terms*—Blumlein, deflagration to detonation transition (DDT), laminar flame, pseudospark, pulse detonation engine (PDE), streamers, transient plasma, turbulent flame.**

I. INTRODUCTION

THE study of methane/air combustion provides fundamental information for the understanding of combustion processes of these and higher hydrocarbons, and is important for applications in propulsion and automotive engines [1]–[4]. Combustion processes are conventionally ignited by high-temperature air (as in diesel engines) or spark discharges, which in turn initiate thermal decomposition of fuels into radicals [5]. Combustion rates can be enhanced if radicals are initially produced by other means in addition to thermal decomposition. For example, external energy sources such as plasma jets [6], [7], high-energy electron beams [8], [9], and excimer laser beams [10], [11] can be injected into the reactive media, and enhancement of combustion rates has been observed with these methods. Simulations predict that direct dissociation of methane and/or oxygen can enhance the combustion rates of methane/oxygen/argon [12] and methane/air [13] mixtures, and theoretical studies [14] also predict that plasma-assisted combustion may, in addition to improving combustion rates, result in reduction of undesirable combustion products such as NO.

For these studies, the transient plasma discharges were comprised of a volume-distributed array of streamers, which persist during approximately 50 ns. The experimental details are described below. Streamers have two distinct regions: 1) a small "head," with a high electric field (100s kV/cm) and low conductivity. In air, a streamer head is effectively a small space-charge region [15]. 2) A "tail" with high conductivity and low electric field (streamer channel). Generally, the streamer velocity and channel radius are of the order of $10^7 - 10^8$ cm/s and 1 mm to 100 μm. Photoionization, electron-impact ionization, and charged particle drift in the high electric field of the streamer head are important in the development and propagation of a streamer [16], [17].

Transient plasma steamers created by pulsed corona discharges can efficiently fill a significant fraction of the gas volume [18], shown in Fig. 1. The streamers persist for a few tens of ns. Quantitative models for streamers are limited because of strong inhomogeneous spatial and temporal characteristics, and remain an important area for study of microscopic processes for reasons that include their application to combustion. Nonequilibrium electrons, however, exist in the head of streamer, where the local reduced electric field $\mathrm{E/N} > 100\ \mathrm{Td}$ [15], and are responsible for direct electron impact excitation, ionization and dissociation [18], [19]. Energetic electrons with high kinetic energies will much more efficiently dissociate fuel and oxidizer molecules into reactive radicals and other species than will quasi-equilibrated electrons, which form as the discharge evolves. As an example of an application of this effect, in previous work, energetic electrons generated in transient corona discharges have been applied to produce highly reactive radicals and ions to remove nitrogen oxides from diesel exhaust, and provided considerably improved efficiency relative to quasi-equilibrated discharges [20].

The ignition of a pulse detonation engine (PDE) is a useful potential application of transient plasma technology. The PDE is attractive because it is potentially a low-cost alternative to turbojet and liquid-propellant rocket engines. Both air breathing and pure rocket modes of PDE operation offer substantial system, materials, and cycle advantages that will mitigate the scalability, operational range, efficiency, and cost limitations of existing engines [21]. Similar to automobile engines, PDEs require reignition for each cycle, and ignited fuel/oxidizer premixed flame must undergo a deflagration-to-detonation transition (DDT) in each cycle and within the engine lenght

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F. Wang, A. Kuthi, C. Jiang, and M. A. Gundersen are with the Department of Electrical Engineering–Electrophysics, University of Southern California, Los Angeles, CA 90089 USA (e-mail: feiwang@usc.edu).

J. B. Liu and P. Ronney are with the Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA 90089 USA.

J. Sinibaldi and C. Brophy are with the Department of Mechanical and Astronautical Engineering, Naval Postgraduate School, Monterey, CA 93943 USA.

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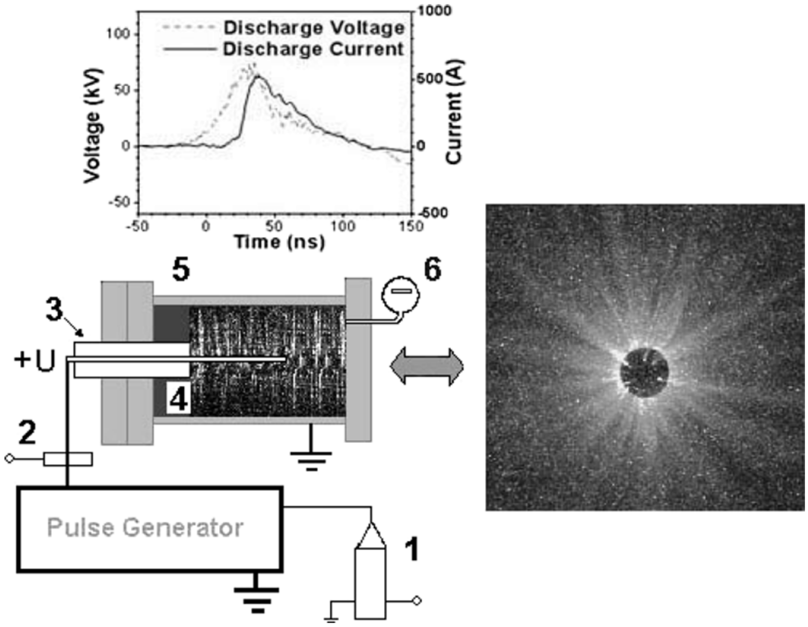

Fig. 1. Schematic of the ignition chamber and electrical measuring system: (1) HV probe; (2) Rogowski coil; (3) nylon insular; (4) stainless steel HV electrode; (5) grounded cylindrical chamber; (6) pressure transducer.

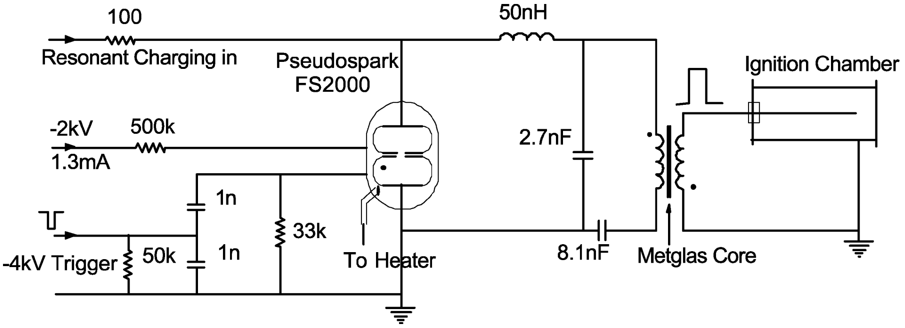

Fig. 2. Pulse generator circuit schematic for transient plasma-assisted ignition experiments.

to realize efficient and maximum propulsion. DDT length and DDT time will determine the lower limits of engine size and operation cycle. Typically, in order to provide constant thrust, a single tube PDE may require operation at 100 Hz. Traditional PDE ignition methods use spark plug ignition, by which an initially laminar flame undergoes a sequence of changes in propagation mechanism into a turbulent flame, and ultimately resulting in a self-sustained supersonic detonation. The laminar-to-turbulent flame transition comprises the majority of the time required for DDT [21]. Therefore, a powerful igniter is necessary for short DDT and a practical PDE. Because the transient plasma can directly generate energetic species over a wide volume, this approach has the potential for effectively creating a turbulent flame during a shorter time. Flow ignition results presented in this paper support this hypothesis.

II. EXPERIMENTAL

A. Pulsed Power

The experimental apparatus used to create transient discharges is a pseudospark switch-based pulse generator [22]. Elements of the circuit schematic are shown in Fig. 2. A resonant-charged lumped element Blumlein is switched by a Pseudospark (FS2000), onto the primary winding of a 1:3 Metglas-polyethylene-foil core pulse transformer to create high-voltage short-duration electric pulses and to maximize the electric field transferred to the reactor. For spark discharge comparisons, traditional spark ignition sources were employed.

Desired pulse shape for transient plasma ignition depends on the geometry of the combustor, ignition chamber as well as the corona electrode. Generally, the inception of pulsed corona at atmospheric pressure requires an external field of the order 10 $\mathrm{kV\ cm^{-1}}$ and a rate-of-rise of the applied pulse voltage of not less than 1 $\cdot\mathrm{kVns^{-1}}$ [23]. In the present experiments, the pulse length is typically ~50 ns, pulse amplitude ~80 kV, energy delivered per pulse 100~800 mJ, depending on the geometry of electrode and ignition chamber.

Discharge current and voltage were measured using a current transformer (Pearson Electronics 6595) and custom-made high-voltage dividers, and were recorded by a digital oscilloscope.

B. Ignition of Quiescent $\mathrm{CH_4}$*/Air Mixtures*

The ignition chamber was a cylindrical stainless steel tube of 63.5 mm in diameter and 200 mm in length. One end plate of the

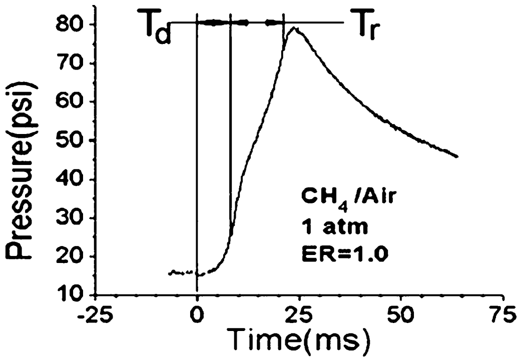

Fig. 3. Pressure histories of CH4/air combustion ignited by transient plasma.

cylinder had ports for gas supplies and vacuum pump, and the other end had transducers for measuring reactant partial pressures and the total gas pressures during combustion. The combustion chamber was kept at ground potential. A steel rod of 3.8 mm diameter and 150 mm long served as the central electrode, insulated from ground, and connected to positive high voltage (Fig. 1). An automotive spark plug (Bosch, platinum, 0.8 mm gap) was used for the spark discharges. The pressure was measured by a pressure transducer (Omega PX-105) and recorded using a digital oscilloscope.

In order to characterize these combustion events, two time periods are defined, as shown in Fig. 3. The delay time, $\mathrm{T_d}$, is the time lapse between the discharge pulse at $\mathrm{t} = 0$ and the pressure reaching 10% of the peak pressure; the rise time, $\mathrm{T_r}$, is the duration between the pressure rising from 10% to 90% of the peak.

C. *Ignition of Flowing* C_2H_4*/Air Mixtures in PDE*

The experiment on flowing ethane/air mixture was performed at the Rocket Propulsion Laboratory of the Naval Postgraduate School, Monterey, CA. Ethylene is typically used by the technical community conducting studies of PDE. Details about fuel choices for PDE are addressed in [24]. Schematic of the experimental setup is shown in Fig. 4. A 20-cm-long ignition chamber was integrated into a 10.1-cm-inner diameter single tube PDE. Due to the high mass flow rate it required the use of a 10-cm diameter perforated Teflon insert, with symmetrically distributed 4-mm holes, placed 2.5 cm from the head-end flange so that the flow field would be more uniform and inhibit the extinction of the combustion process. Premixed C_2H_4-air mixtures were injected into the ignition chamber from six horizontal ports equally spaced on the head-end flange. An aluminum converging/diverging choke with a 2.54-cm orifice was placed after the ignition chamber to provide a restriction and keep the local velocity in the ignition chamber below 15 m/s. This allowed the local ignition chamber pressure to be increased to as high as 725 kPa. The initial mixture temperature in the ignition chamber could be varied between 280 and 400 K through the use of electrical heaters. Four 2-cm-long steel needles were added at the 1/3 and 2/3 axial location of the 7.5-cm-long high-voltage electrode to bring the anode closer to ground. A high frequency pressure transducer (PT0) was installed centrally along the ignition chamber wall to detect the initial pressure and pressure rise within the ignition chamber. Spirals were added to accelerate expanding combustion products in order to shorten DDT length.

Testing for the high mass flow conditions was limited to C_2H_4–air mixtures at an equivalence ratio of 1.44 and a mass flow rate range of 0.10–0.35 kg/s. Experiments were also run for the conditions with an MSD model 6A conventional capacitive discharge spark system, which utilized a nominal ignition energy of 150 mJ.

III. RESULTS

A. *Quiescent Ignition Results*

The ignition delay times and pressure rise time after ignition at atmosphere pressure were evaluated with respect to different equivalence ratios, The equivalence ratio was varied between $\phi = 0.8$ and 1.4 for CH_4–air mixture.

Transient plasma compared with spark ignition results in a factor of 2 to 3 shorter ignition delay time and pressure rise time as illustrated in Fig. 5. The enhancement is more prominent at low equivalence ratio, which leads to cleaner combustion. Higher peak pressures and lower residual pressures can also be achieved by transient plasma ignition indicating that transient plasma ignition results in higher combustion efficiency.

B. *Flow Ignition Results*

The results presented are for a constant equivalence ratio of 1.44 and a fixed mass flow rate of 0.35 kg/s for C_2H_4/air. The trends shown in Fig. 6 are typical for flow rates above 0.20 kg/s and the 0.35 kg/s case depicted is representative of all flow conditions in the PDE system. Both a capacitive discharge spark plug and transient plasma ignition system were evaluated at comparable energy levels (150–500 mJ).

The important observation to be made from Fig. 6 is that the characteristic ignition delay time for the transient plasma ignition system appears to be insensitive to initial reactant temperature for the flow rate and corresponding pressure and turbulence intensity. Since the conditions are representative of an actual flowing system, the relatively low delay times near 2 ms are applicable to the development of a fuel–air initiator. Corresponding DDT times for this system were only 200–300 μs beyond the ignition delay times and reveal that the obvious impediment on the generation of a detonation wave is the initial ignition sequence which leads to the generation of strong pressure waves. Hence, reducing the observed ignition delay times is important. At the same time, 2-ms ignition delay makes it possible for PDE to be operated at 100-Hz repetition rate, at which there is only 10 ms per cycle.

IV. DISCUSSION

The combustion processes initiated by the transient plasma-produced streamers, at nominal temperatures, are attributed to the voluminous distribution of streamers, and also the highly reactive chemical species produced by energetic electrons. There are a number of possible chemical reaction processes, and an

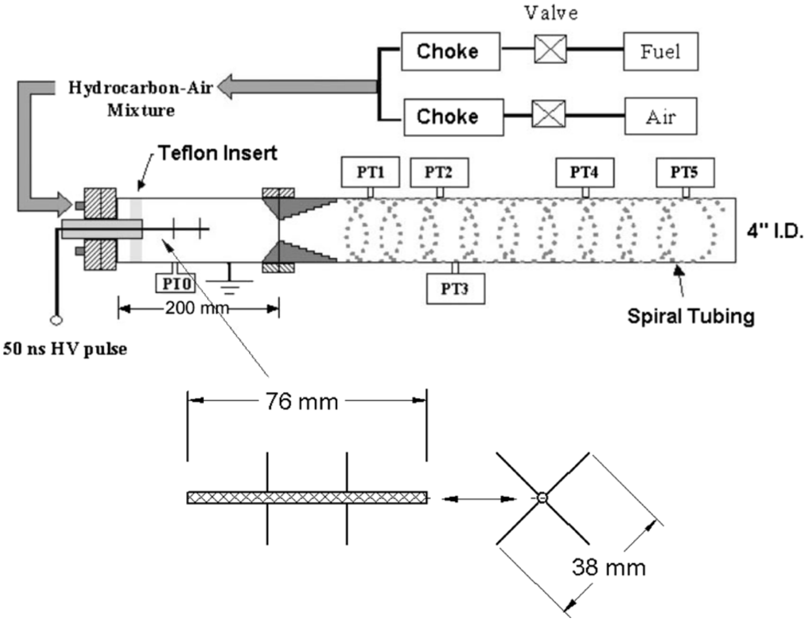

Fig. 4. Schematic of PDE ignition system. PT stands for pressure transducer.

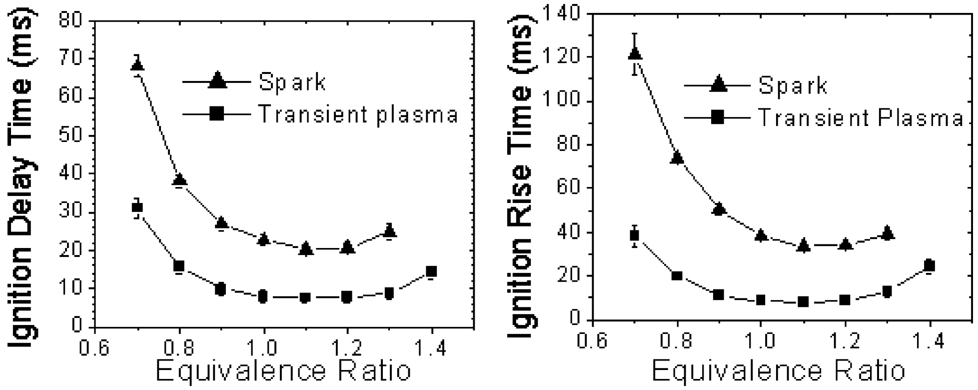

Fig. 5. Results of ignition delay time and rise time.

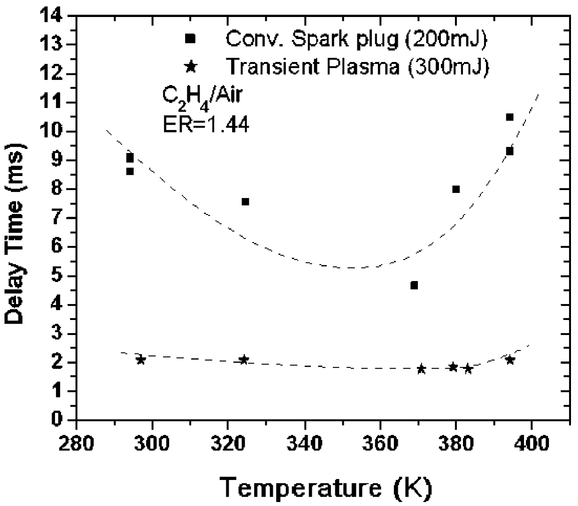

Fig. 6. Ignition delay time versus temperature for a C2H4/air mixture $(\mathrm{ER} = 1.44)$ after both spark plug and transient plasma ignition.

analysis of the detailed plasma chemistry is beyond the scope of this work, thus detailed understanding of electron impact processes is incomplete. However, it is nevertheless worthwhile to consider the production of excited H atom by [19], [25]

$$\mathrm{C_nH_m} + \mathrm{e} \rightarrow \mathrm{C_nH_{m-1}} + \mathrm{H}^* + \mathrm{e}. \tag{1}$$

The excited H atom produced by dissociation through reactions (1) may carry several electronvolts of kinetic energy, and the hydrogen will be added to the fuel mixture.

An additional primary dissociative reaction that may contribute to the enhanced combustion process when ignited by a corona discharge is

$$\mathrm{O_2} + \mathrm{e} \rightarrow \mathrm{O(^1D)} + \mathrm{O(^3P)} + \mathrm{e}. \tag{2}$$

The threshold for reaction (2) is expected to occur at 7.0 eV, similar to the threshold of photodissociation [26]. Modeling calculations [27] show that reaction (2) is the major process in discharge of atmospheric $\mathrm{O_2}$ at $E/n > 100\ \mathrm{Td}$. $\mathrm{O(^1D)}$ reacts very rapidly with most $\mathrm{C_nH_m}$ molecules at room temperature to produce OH which is a key radical leading to chain-branching combustion reactions [28].

The input energies (<0.9 J) in corona discharges are comparable to conventional ignition systems. The current results demonstrate that flame ignition by transient plasmas generated by high electric fields may provide an energy efficient means of increasing initial combustion rates. In addition to pulse detonation engines, this relatively simple technology has potential for a wide range of practical applications including internal combustion engines, gas turbines, and rocket propulsion systems. It is anticipated that study of electron dissociation of fuel molecules in similar transient plasma systems will be a useful topic for future research.

V. SUMMARY

Nanosecond transient plasmas have been applied to the ignition of hydrocarbon–air mixtures under quiescent and dynamic fill conditions and within combustor geometries representative of pulsed detonation engines. Reduction of ignition delay times were observed for both experiments, of the order 2–3 for quiescent studies and 4–5 for flowing PDE experiments. This enhancement is more prominent at low equivalence radio and dynamic fill conditions (almost a factor of 5). The transient plasma ignition strategy provides an accelerated combustion sequence leading to the rapid generation of strong pressure waves and transition of laminar flame to turbulent flame, significantly shorten the DDT time.

The conditions evaluated for the high flow rate tests are representative of dynamic fill conditions existing in fuel–air PDE systems under development and the observations to date on the transient plasma ignition system appear to provide a promising technology for the meeting the requirements for a practical fuel–air initiator.

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Fei Wang (M’03) was born in Hebei, China, in 1979. He received the B.S. degree in physics from Jilin University, China, in 2001. Since 2001, he has been with the Department of Electrical Engineering-Electrophysics, University of Southern California, Los Angeles, where he is engaged in projects related to pulsed power technology and its applications for the Ph.D. degree in physics. In particular, he has concentrated his studies on pulsed power systems for aircraft engine ignition and combustion control.

He has authored and coauthored 16 journal and conference papers.

Mr. Wang is a Member of American Institute of Aeronautics and Astronautics (AIAA).

J. B. Liu, photograph and biography not available at the time of publication.

J. Sinibaldi, photograph and biography not available at the time of publication.

C. Brophy, photograph and biography not available at the time of publication.

A. Kuthi, photograph and biography not available at the time of publication.

C. Jiang, photograph and biography not available at the time of publication.

P. Ronney, photograph and biography not available at the time of publication.

Martin A. Gundersen (M'74–SM'83–F'91) received the B.A. degree from the University of California, Berkeley, in 1965 and the Ph.D. degree from the University of Southern California, Los Angeles, in 1972.

He is a Professor in the Department of Electrical Engineering-Electrophysics at the University of Southern California.