2004-01

Transient Plasma Ignition of Hydrocarbon-Air Mixtures

Wang, F.; Jiang, C.; Kuthi, A.; Gundersen, M.A.; Sinibaldi, C. Brophy and J.0.; Lee, L.C.

AIAA

http://hdl.handle.net/10945/69028

42nd AIAA Aerospace Sciences Meeting and Exhibit
5 - 8 January 2004, Reno, Nevada

AIAA 2004-834

AIAA-2004-0834

Transient Plasma Ignition of Hydrocarbon-Air Mixtures in Pulse Detonation Engines

F. Wang, C. Jiang, A. Kuthi and M. A. Gundersen
Department of Electrical Engineering,
University of Southern California, Los Angeles, CA 90089-0271

C. Brophy and J. O. Sinibaldi
Department of Aeronautics and Astronautics,
Naval Postgraduate School, Monterey, CA 93943

L. C. Lee
Department of Electrical and Computer Engineering,
San Diego State University, San Diego, CA 92182

Abstract

A transient plasma ignition system has been demonstrated to substantially reduce the ignition delay and detonation-to-detonation transition times for ethylene-air and propane-air mixtures under dynamic fill conditions. The effects initial conditions including equivalence ratio, a temperature range of 280K to 430K, and pressure range of 1 to 6 atm were evaluated. Ignition delays were reduced by up to a factor of 5 and the corresponding deflagration-to-detonation time scales were observed to decrease accordingly when compared to conventional capacitive discharge systems. The substantial reduction of the ignition delay times resulted in the generation of strong pressure waves which inherently steepened into shock waves quickly and in a short distance. Although direct initiation of a detonation wave was not obtained, the sub sequential use of a Shchelkin spiral was able to rapidly and reliably accelerate the combustion driven shock waves to detonations within practical distances. The efficiency and performance of the transient plasma ignition strategy will likely contribute to the development of fuel-air detonation initiators.

Introduction

A key issue for the development of pulse detonation engines (PDE) is to design an ignition system that consumes low-energy, provides a rapid/short run-up distance to detonation, and has reproducible shot-to-shot performance. Currently, many investigators are using various forms of conventional capacitive discharge spark systems to initiate the chemical reactions in PDEs[1-3]. References 1 and 2 identify the minimum energies required for a capacitive discharge system to obtain successful deflagration to detonation transitions (DDT) at various stoichiometries in Hydrocarbon/Oxygen/Nitrogen mixtures in a 7.5 cm diameter 1.2m long detonation tube with quiescent mixtures. Those studies investigated the effects of energy deposition and mixture composition on detonation run-up distances. Low energy consumption (70 mJ per spark) and ease of implementation are the advantages for this type of pulsed ignitors. However, previous work on the ignition of hydrocarbon/air mixtures with conventional capacitive discharge spark systems, revealed impractical detonation transition lengths and timescales for use in PDE systems without the use of oxygen enrichment or excessive turbulence generating devices [1-4]. Transient plasma ignition (TPI) of premixed hydrocarbon-air mixtures under constant volume conditions have shown improved performance compared to the conventional spark discharge by yielding shorter characteristic pressure rise times[5] at the same initial conditions. This indicates that highly active radicals with fast chemical reaction paths are created and that transient

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

plasmas generated by high electric fields can rapidly initiate combustion with low input energies (less than 1 J) comparable to conventional spark ignition systems. Therefore, this transient plasma, characterized as a pulsed corona discharge, likely provides a better ignition sequence for PDEs which are very sensitive to cycle timing. This paper presents experimental results using a corona discharge system to ignite C_2H_4-air and C_3H_8-air mixtures in a pulse detonation combustor.

Experimental Setup

The experiment was performed at the Rocket Propulsion Laboratory of the Naval Postgraduate School. A schematic of the experimental setups used is shown in Figure 1. The ignition chamber consisted of a 22 cm long stainless steel cylinder with an inner diameter of 10 cm. The electrode consisted of a 4 mm diameter stainless steel bolt of various lengths between 5 cm and 15 cm. It was attached to the head-end of the combustor, ran axially along the centerline of the ignition chamber, and was insulated by Teflon from the grounded chamber. A voltage pulse with magnitudes higher than 85 kV and a pulse duration of 50 ns was applied to the center electrode. A synthetic Blumlein transmission line switched by a Pseudospark was used to provide the high voltage pulse through a 1:3 Metglas-polyethylene-foil core pulse transformer [6]. A high voltage pulse generator was used to provide microsecond voltage pulses, synchronized, by a delay generator with the trigger signal to form the nanosecond pulse-forming network. A digital oscilloscope was used to record the discharge voltage and current through a 1:1000 voltage divider and a pulsed current transformer (Pearson Electronics 6595), respectively.

The low mass flow experiments injected premixed hydrocarbon-air mixtures into the ignition chamber from 6 axially symmetric ports located 5 cm away from the head wall of the ignition chamber to create a homogeneous mixture. The 6 injection ports were designed to minimize large recirculation zones, which could affect the local instantaneous equivalence ratio since the experiment was conducted under dynamic fill conditions and not quiescent. A 131 cm long, 10 cm diameter stainless steel combustor section was attached downstream of the ignition chamber. Five pressure transducers with response times of 2 μs were installed along the walls

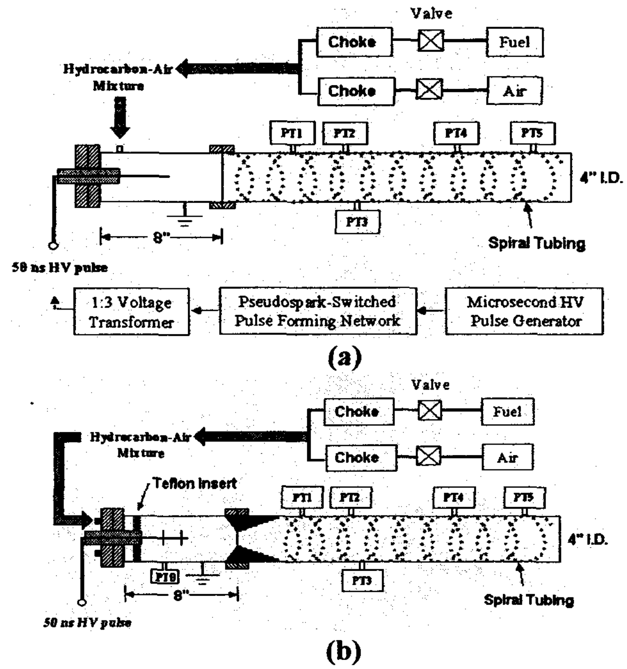


Figure 1: The experimental setup for the transient plasma ignition system; (a) Low mass flow (b) High mass flow injection setup

at the following axial locations: 42.5 cm, 87.9 cm, 95.6 cm, 111.2 cm, and 144.2 cm away from the head wall of the ignition chamber. Since the internal diameter of the combustor was 10 cm, these locations correspond to x/D values of 4.25, 8.79, 9.56, 11.12, and 14.42 respectively. The transducers monitored the temporal and spatial pressure profile along the detonation tube axis. A 75 cm long Shchelkin spiral consisting of 6mm diameter thick coils, a 9.8 cm diameter coil, and a pitch of 8 coils / meter was installed along the combustor inner walls to study the deflagration-to-detonation transitions in C_2H_4-air and C_3H_8-air mixtures.

The DDT delay times were evaluated with respect to different ignition conditions, including the equivalence ratio, the mixture temperature, and the mass flow rate which generally varied the level of turbulence. The equivalence ratio was varied between ϕ = 0.8 and 1.5 for both C_2H_4-air and C_3H_8-air mixtures. The mixture temperature was varied from 285 K to 480 K in order to study the effects of increasing the chemical kinetic rates on DDT delay times and DDT lengths (detonation run-up distance.) The mass flow rate was varied, on a limited scale, from 10 g/s to 25 g/s for the low mass flow tests to evaluate the effects of turbulence on the initial chemical reaction, pressure rise, and subsequent deflagration-to-detonation transition process.

The high mass flow rate experiments required the use of a 10.1 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 extinguishing of the combustion process. Premixed C_2H_4-air mixtures were injected into the ignition chamber from 6 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 280K and 400K 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. An additional high frequency pressure transducer was installed centrally along the ignition chamber wall to detect the initial pressure and pressure rise within the ignition chamber.

Due to time constraints, 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 kg/s to 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.

Results

Low Mass Flow Tests

The low mass flow tests evaluated temperature and equivalence ratio effects up to aggregate mass flow rates of approximately 25 g/s and were ultimately limited by blow out limits within the ignition chamber. The characteristic parameters describing the initial conditions, included the fuel-air mixture equivalence ratio, the ignition gas temperature, and the initial mass flow rate and were studied for both ethylene-air and propane-air mixtures. The discharge voltage applied was 86 kV or 74 kV with a fluctuation error of 8% or 13% for C_2H_4-air or C_3H_8-air mixtures, respectively. The voltage difference is due to the impedance difference of different gases. The corresponding energy for each shot was 611 mJ or 565 mJ for C_2H_4-air or C_3H_8-air mixtures, respectively.

The combustion event initiated with the transient plasma ignitor was immediately evident at the first transducer as strong pressure waves with 200 kPa to 1 MPa maximum values. The waves were often further accelerated in the spiral section to the Chapman-Jouguet (C-J) values. Figure 2 shows typical wave speed behavior along the combustor axis for three different equivalence ratios. The wave speed was calculated by dividing the distance between two transducers by the time-of-arrival for the pressure signals. The time-of-arrival was defined to be when the pressure signals reached 10% of their peak value. From the wave speed measurements and pressure amplitudes, it was determined that the combustion wave typically transitioned to a detonation between the 3rd and 4th transducer locations for all but the fuel lean cases evaluated. The average detonation wave speeds were approximately 25% above the C-J values between the 3rd and 4th transducers, but then relaxed to near the C-J values between the 4th and 5th transducers. The inability of the 0.8 equivalence ratio conditions to transition to a detonation is primarily due to the increased characteristic delay times and corresponding slower chemical kinetics for the fuel lean conditions. Although the fuel lean condition did not transition to a detonation, the presence of a strong combustion driven shock is evident by the observed wavespeeds.

Additional pressure transducers would have allowed a more definitive determination of transition location and wave velocity, but that was not the primary goal of this test series which was to determine the ignition delay time and capability to generate a combustion driven shock wave by the transient plasma ignition system. Once the combustion driven shock wave was generated, it could often be further accelerated by the addition of a spiral tube, or other wall turbulence-generating device, along the inner wall of the combustor.

In this paper, the characteristic ignition delay time is defined as the time from the high voltage appearing on the center electrode to when the first transducer at x/D=4.25 observes a pressure rise of 100 kPa. This also measures the average flame propagation speed.

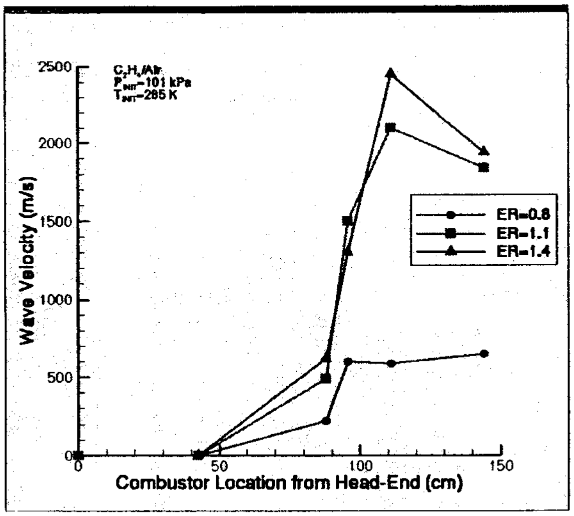


Figure 2: Wave speed vs. Combustor Location for C_2H_4-Air Mixtures with TPI system

As the delay time is reduced, the average wave speed increases and the resulting pressure also increases due to acoustic waves, which steepen quickly. The peak pressure is defined as the maximum value of a temporal pressure profile monitored by transducers.

The characteristic delay time and observed peak pressures at transducer #1 were investigated for C_3H_8-air and C_2H_4-air mixtures with a constant initial gas temperature of 288 K and corresponding reactant mass flow rates of 5 and 9 g/s, respectively. The minimum delay time and the maximum pressure amplitudes were obtained at an equivalence ratio of 1.2 for C_2H_4-air mixtures and 1.1 for C_3H_8-air mixtures. For the C_2H_4-air mixtures, the minimum delay time and the maximum peak pressure were measured to be 9.8 ms and 144 psig (1.1 MPa) respectively. For C_3H_8-air mixtures, the minimum delay time was 20 ms and the maximum peak pressure, 48 psig. The increased delay times are due to the slower chemical kinetics associated with propane and ultimately result in a lower observed peak pressure than those observed for C_2H_4-air mixtures. The data plotted in Figure 3 and the corresponding errors are estimated to be +/- 0.250 ms and +/- 6 psi.

The temperature influence on the characteristic parameters was also evaluated for C_2H_4-air and C_3H_8-air mixtures keeping the equivalence ratio and the reactant mass flow rate constant. The optimum equivalence ratio was chosen for both mixtures and

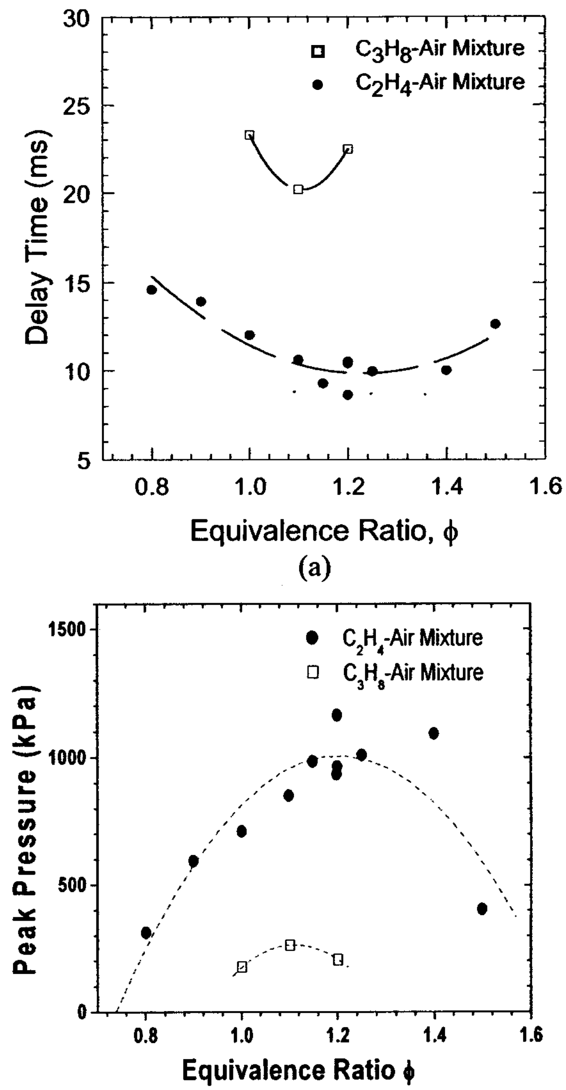
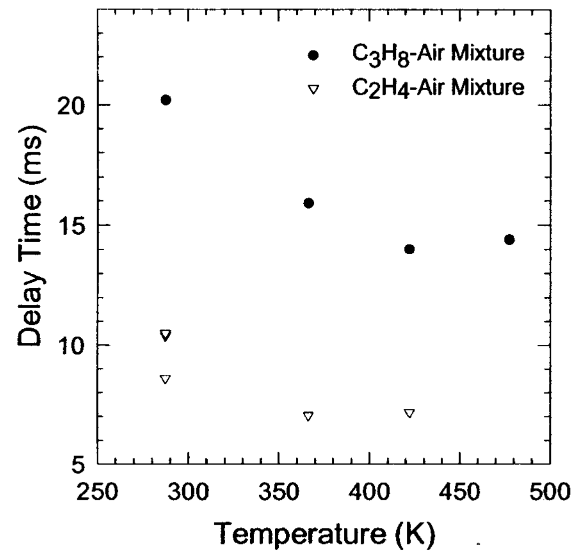


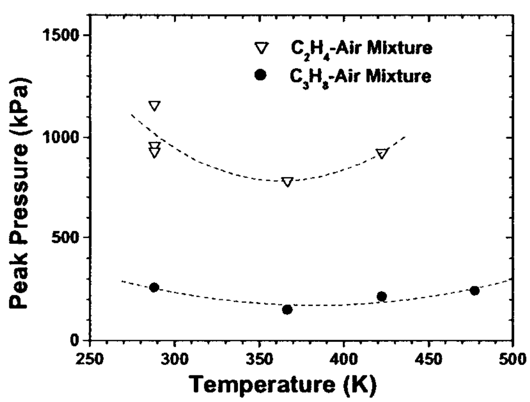
Figure 3: The delay time and observed peak pressure at PT#1 with respect to the equivalence ratio at 285K for C_2H_4-air and C_3H_8-air mixtures with TPI system.

was fixed at 1.2 for C_2H_4-air and a value of 1.1 for C_3H_8-air. The reactant mass flow rate was held constant at approximately 9 g/s. Temperature effects on the characteristic ignition delay time and corresponding peak pressure are shown in Figure 4. Increasing the gas temperature reduced the characteristic delay time without much influence on the peak pressure for both the C_2H_4-air and C_3H_8-air mixtures. As low as 7 ms and 14 ms delay time for the C_2H_4-air and C_3H_8-air mixtures, respectively, were reached when the temperature was increased up to 422 K. The apparent "leveling off" of both parameters is due to the conflicting effects of increased speed of sound of the reactant mixture and the increased chemical kinetics rates due to the increasing temperature. As the kinetic rates increase with temperature, the speed of sound increases as well. Thus allowing acoustic energy to propagate more quickly out of the combustor which inhibits a steepening of the pressure waves into a shock wave.

The gas dynamic influence on the ignition processes was evaluated over a limited range for the low mass flow tests. The initial reactant temperature was held constant at 288 K and at constant equivalence ratio of 1.2 for the C_2H_4-air mixtures.



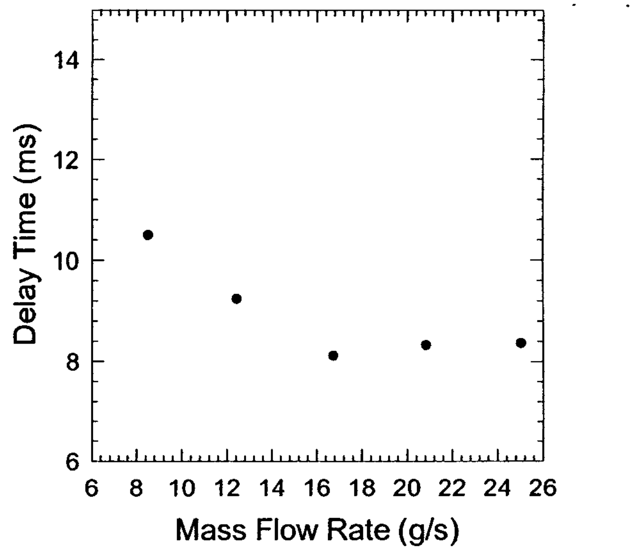
(a)



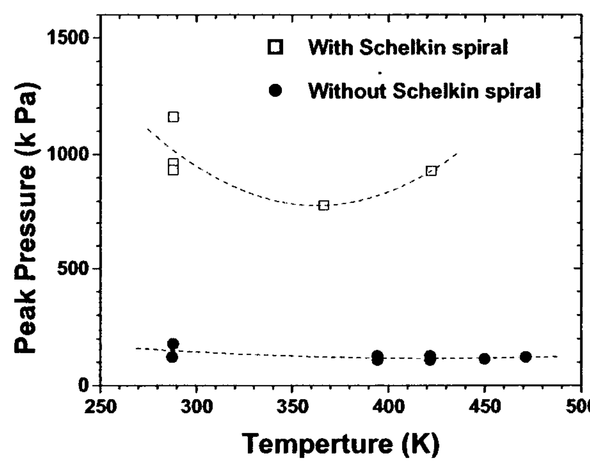
(b)

Figure 4: The temperature influence on (a) the delay time and (b) the peak pressure for TPI system. ER=1.2 for C_2H_4-air mixtures and 1.1 for C_3H_8-air mixture.

The reactant mass flow rates were varied from 8.5 g/s to 25 g/s and the results are shown in Figure 5 (a) and (b). As expected, the characteristic delay time decreased as the flow rate increased up to 16.7 g/s and then remained almost constant as the mass flow rate further increased. The behavior above a flow rate of 18 g/s was believed to be due primarily to the increased local velocities and global flow field effects. This observation resulted in the modification of the ignition chamber section for the high flow rate test conditions.



(a)



(b)

Figure 5: The mass flow rate influence on (a) the delay time and (b) the peak pressure at room temperature (288 K) and C_2H_4-Air mixture with an equivalence ratio of 1.2 for the TPI system.

High Mass Flow Tests

Results for the high mass flow conditions are limited to one equivalence ratio due to time constraints on use of the hardware. The results presented are for a constant equivalence ratio of 1.44 for C_2H_4/Air and a fixed mass flow rate of 0.35 kg/s. The trends shown in Figure 6 are typical for flow rates above 0.20 kg/s and the 0.35 kg/s case depicted is representative of flow conditions with a PDE system. Both a capacitive discharge and transient plasma ignition system were evaluated at comparable energy levels (150 – 500 mJ).

The important observation to be made from Figure 6 is that the characteristic ignition delay time for the TPI 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 very applicable to the development of a fuel-air initiator. Corresponding DDT times for this system were only 200-300 microseconds 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, the importance of reducing the observed ignition delay times.

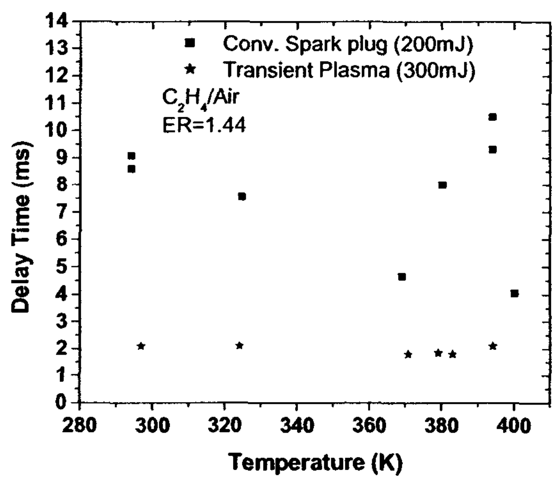


Figure 6: Ignition delay time versus temperature for an C2H4/Air mixture (ER=1.44) after both capacitive discharge and transient plasma ignition.

Discussion

The combustion processes initiated by corona discharges at nominal temperatures are attributed to the highly reactive chemical species produced by energetic electrons (with energies above 10 eV) [5]. Although there are a number of possible chemical reaction processes, Although an analysis of the detailed plasma chemistry is beyond the scope of this work and remains an important topic for future research, it is nevertheless worthwhile to consider the production of excited H atom by [7,8]:

$C_nH_m + e \rightarrow C_nH_{m-1} + H^* + e$ (1)

The excited H atom produced by reaction (1) may carry several eV of kinetic energy. The other primary process that may contribute to the combustion process when ignited by a corona discharge is:

$O_2 + e \rightarrow O(^1D) + O(^3P) + e$ (2)

The threshold for reaction (2) is expected to occur at 7.0 eV, similar to the threshold of photodissociation [9]. Modeling calculations [10] show that reaction (2) is the major process in discharge of atmospheric O_2 at E/n > 10-15 V cm2. $O(^1D)$ reacts very rapidly with most C_nH_m molecules at room temperature to produce OH which leads to chain-branching combustion reactions[11].

The input energies (< 0.9 J) in corona discharges are far less than the heat release from combustion and are representative of 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 may be anticipated that study of electron dissociation of fuel molecules in similar transient plasma systems will be a useful topic for future research.

Summary

Nanosecond transient plasmas have been applied to the ignition of hydrocarbon-air mixtures under dynamic fill conditions and within combustor geometries representative of pulsed detonation engines. Although the transient plasma ignition strategy provides an accelerated combustion sequence leading to the rapid generation of strong pressure waves, the shock ultimately generated by the expanding combustion products must still be accelerated by conventional means. Detonations were successfully obtained for stoichiometric and fuel-rich ethylene-air mixtures when wall turbulence was introduced after the ignition chamber through the use of a spiral. This is the first time a nanosecond corona discharge has been used as an ignitor for hydrocarbon-air detonations in a pulsed combustor. It has been demonstrated that this new technology is better than conventional capacitive discharge spark systems by providing a stronger initial ignition source while consuming comparable energy and resulting in reducing the characteristic ignition delay and subsequent DDT time by at least a factor of 3. The minimum delay time and the maximum peak pressure were obtained at equivalence ratios of 1.2 and 1.1 for ethylene-air and propane-air mixtures, respectively. Generally, increasing the initial gas temperature decreases the ignition delay time due to the well known dependence of reaction rates on temperature. Increasing the injection rate of the premixed reactants also decreases the delay time, which is likely due to the increasing turbulence intensity associated with those rates. Therefore, over the temperature range evaluated and for the lower mass flow rates, elevated initial reactant temperature and increasing mass flow rates tended to yield better conditions for rapid and successful detonation-to-detonation transitions. The effects of initial reactant temperature on the ignition delay time diminished once the mass flow rates exceeded approximately 0.2 kg/s corresponding to an initial chamber pressure of near 4 atm, revealing the importance of pressure and turbulence intensity on accelerating the combustion process. The initial reactions in the transient plasma ignition sequence appear to be generally insensitive to initial reactant temperature since the strategy relies more on a electronic-type ignition event versus thermal. The observation that rise time was affected by higher temperatures and not delay time seems to support this line of thinking.

It should be reiterated that 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 TPI system appear to provide a promising technology for the meeting the requirements for a practical fuel-air initiator.

Further quantitative study on the effects of the turbulence intensity and mass flow rates will be conducted in future work. Moreover, a thorough investigation on the transient ignition physics deserves to be conducted, including the temporal and spatial composition development by optical diagnostics.

Acknowledgements

This work is supported by the U. S. Office of Naval Research under Grant no. N00014-00-1-0098, and Grant no N00014-03-WR-20159, and by the U. S. Air Force Office of Scientific Research under Grant no. F49620-01-1-0322.

References

[1] Robinson, J.P., "Influence of Ignition Energy, Ignition Location, and Stoichiometry on the Deflagration-to-Detonation Distance in a Pulse Detonation Engine," Masters' Thesis, Naval Postgraduate School, Monterey, CA, (2000)

[2] Sinibaldi, J.O., Brophy, C.M., and Robinson, J.P., "Ignition Effects On Deflagration-To-Detonation Transition Distance In Gaseous Mixtures," AIAA paper No. 2000-3590, 18th AIAA/ASME/SAE Joint Propulsion Conference, Huntsville, AL (2000)

[3] Lee S.-Y., Conrad C., Watts J., Woodward R., Pal S., and Santoro R.J., "Deflagrationto-Detonation Transition Study Using Simultaneous Schlieren and OH PLIF Images,"Joint Propulsion Conference, AIAA Paper 2000-3217, 2000.

[4] Schauer, F., Stutrud, J., Bradley, R., "Detonation Initiation Studies and Performance Results from Pulsed Detonation Engine Applications," AIAA Paper 2001-1129.

[5] Wang, F., Kuthi, A., Gundersen, M.A., Lui, J.B., Ronney, P.D., and Lee, L.C., "Premixed Flame Ignition by Transient Plasma Discharge," 29th International Symposium on Combustion, Combustion Institute, July 21-26, 2002, Sapporo, Japan.

[6] A. Kuthi, J. Liu, C. Young, and M. Gundersen, "Pseudospark Based Pulse Forming Circuit for Transient Plasma Ignition Systems," 14th International Pulsed

Power Conference, Dallas, TX, June 15-18, 2003.

[7] Y. P. Raizer, *Gas Discharge Physics* (Springer-Verlag, Berlin, 1997); W. J. Yi and P.F. Williams, J. Phys. D : Appl. Phys. **35**, 205 (2002).

[8] S. Motlagh and J. H. Moore, J. Chem. Phys. **109**, 432 (1998).

[9] L. C. Lee, T. G. Slanger, G. Black, and R. L. Sharpless, J. Chem. Phys. **67**, 5602 (1977).

[10] E. Eliasson and U. Kogelschatz, J. Phys. B: At. Mol. Phys. **19**, 1241 (1986).

[11] S. T. Amimoto, A. P. Force, R. G. Gulotty, Jr., and J. R. Wiesenfeld, J, Chem. Phys.**71**, 3640 (1979).