Characterization of a Corona Discharge Initiator Using Detonation Tube Impulse Measurements

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Experiments were carried out to determine the effectiveness of a transient plasma, i.e, corona discharge, to initiate a detonation in a short tube. A high-voltage pulse generator used a pseudo-spark switch to discharge a capacitor through a transformer connected to electrodes in the combustion initiator section. The resulting voltage pulse (90 kV for 50 ns) produced a plasma discharge consisting of many radial streamers. The transient plasma initiated low-speed combustion, a deflagration, which can transition to detonation if the mixture is sufficiently sensitive. In some tests, turbulence-generating obstacles were used within the detonation tube to promote the transition from deflagration to detonation. The corona discharge was slightly more effective than a standard internal combustion engine spark plug initiating combustion that will transition to detonation. In all cases, the use of turbulence-generating obstacles significantly improved the effectiveness of detonation initiation as had been found previously in Cooper et al., J. Propulsion Power 18(5), 1033-1041, 2002. The corona discharge was an excellent method to achieve very rapid combustion of the region near the electrodes but additional means appeared to be needed to accelerate the resulting flame to a detonation for mixtures with greater than 40% nitrogen dilution.

Nomenclature

S_u Laminar burning velocity, cm/s
E Expansion ratio
V_f Flame speed, m/s
V_{cj} Detonation velocity, m/s
τ_{s_u} Characteristic combustion time, ms
τ_{cj} Characteristic detonation time, ms
τ_{ddt} Deflagration to detonation transition time, ms
τ_r Characteristic unburned reactant expansion time, ms
τ_p Characteristic burned product expansion time, ms
τ_v Characteristic turbulent combustion time, ms

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I. Introduction

Efficient, low-energy detonation initiators are key issues in pulse detonation engine (PDE) design.[1] This is largely because the amount of energy[2] (200 kJ) needed to directly initiate insensitive mixtures (JP-10-air, propane-air) would require very robust systems that are not practical for PDEs. Deflagration to detonation transition (DDT) is a very efficient way to initiate detonations in mixtures[3] but the use of turbulence-generating obstacles has been shown to decrease impulse performance.[4] Initiation systems that can minimize the initiation energy and impulse losses are much desired.

The transient plasma ignition device developed for initiation at the University of Southern California has been used in various configurations to initiate detonations in static and dynamically filled PDE's.[5] A high-voltage pulse generator uses a pseudo-spark switch to discharge a capacitor through a transformer connected to electrodes in the initiator. The transient discharge that ensues is in the form of high energy electron streamers that readily ignite combustible mixtures. In the configuration studied here, the device discharges a couple of joules of energy per pulse. One of the advantages of the plasma initiator is its ability to reduce the residence time of the low-speed combustion stage.[5] This can benefit PDEs by minimizing the DDT time.

The present study seeks to characterize the effectiveness of the pulsed corona discharge initiator in two ways. The first is to determine its ability to directly initiate detonations in insensitive mixtures as well as in the presence of obstacles. The second is to quantify the reduction in DDT time that would result from minimizing the slow combustive stages of the DDT process. In all cases, a spark plug initiation system is used for the control experiments of this study.

II. Experimental Details

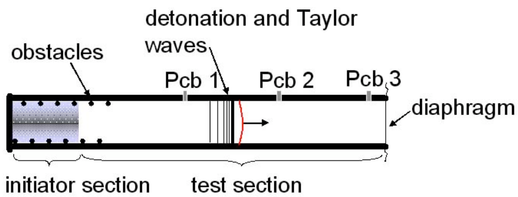
The experiments were performed in a cylindrical tube that consisted of a 20 cm long by 100 mm diameter initiator section and a 1.0 m long by 76.2 mm diameter test section (Fig. 1a). The facility was suspended by cables and operated as a ballistic pendulum. Impulse was determined using the ballistic pendulum method[4] by video recording the swing and measuring the maximum deflection. The test section was equipped with three pressure transducers, spaced 19 cm apart, to measure the pressure histories and detonation velocity. The initiator section, detailed in Fig. 1b, was configured in two ways. First, using the plasma initiator, a center electrode could be placed axially in the initiator section corresponding to the top image. The center electrode could be equipped with various needles to optimize the streamer profile.[5] Second, a spark plug could be placed at the initiator endwall, corresponding to the bottom image. A stoichiometric ethylene-oxygen mixture with varying nitrogen dilution, denoted by the symbol β, was used. For these experiments $1 < \beta < 11.28$. The upper limit of β corresponds to a stoichiometric ethylene-air mixture.

The two sections were linked by an insulating flange to protect the instrumentation from the high-voltage discharge. The current studies examined varying the obstacle configuration to find the maximum nitrogen dilution level for which a detonation could be initiated. Impulse measurements were used to compare the relative effectiveness of the plasma initiator to that of a conventional spark plug with a low energy (<100 mJ) arc discharge.

III. Results

A. Characterization of the Corona Discharge Initiator

The pulsed corona discharge initiator makes use of transient plasma as a means of initiation.[6] The transient plasma is characterized by radial streamers that occur during the breakdown of the gas. The streamers are a transitional plasma phase[7] that lasts for about 50 ns until an arc is formed. Each streamer is comprised of a small streamer head with a large-magnitude electric field and a column of plasma with a low-magnitude electric field. Figures 2a & b are pictures of streamers in a corona discharge and an arc in spark discharge, respectively.[8] The pictures illustrate a key difference between the two mechanisms; streamers occur in large



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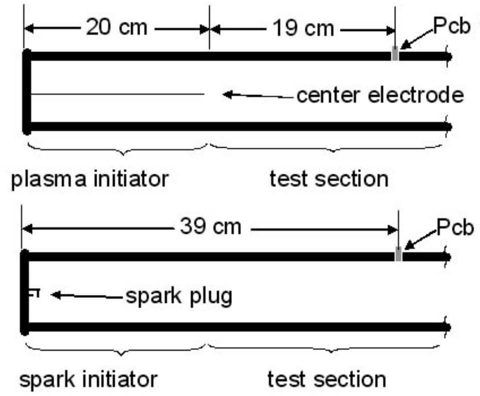
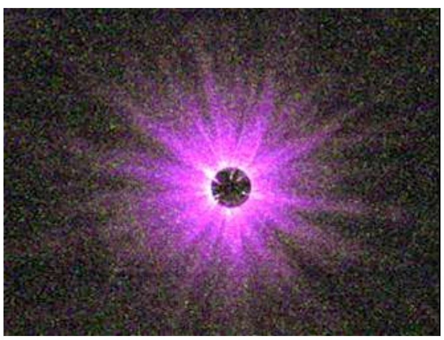


(b)

Figure 1. (a) Schematic of the experiment. (b) A schematic of the initiator section configuration and distance to the first pressure transducer. Top: Transient plasma initiator. Bottom: Spark plug.

numbers that occupy a volume, whereas an arc consists of a single-channel discharge.



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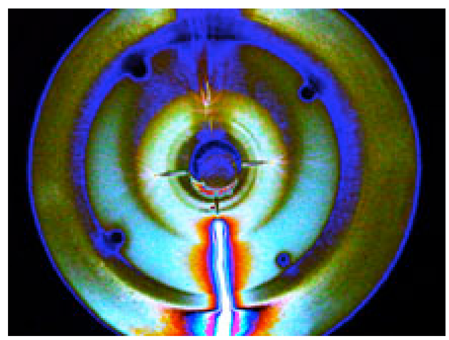


(b)

Figure 2. (a) An image of streamers during a pulsed corona discharge. (b) An image of an arc from a spark discharge. The arc is formed between a needle on the center electrode and the bottom wall of the initiator. It is the overexposed portion of the image. The images are from J. Liu et al., IEEE Transactions on Plasma Science, submitted for publication

The electron energy in a pulsed corona discharge is on the order of 10-20 eV.[9] This is much closer to the ionization and dissociation levels of many molecules when compared to arc discharge electron energies which are on the order of 1 eV.[6]

The electrical characteristics of both initiation systems are examined in Fig. 3. The plots show the voltage and current as a function of time. Both systems exhibit oscillatory motions. The energy of the transient plasma discharge is calculated to be 3.77 J. The energy of the spark plug discharge is 46 mJ. The duration of each pulse is on the order of 1 μs. The spark gap is about 3 mm while the gap between the center electrode and the wall of the initiator section is 8 mm. When comparing both initiation systems, one should keep in mind the two order of magnitude energy difference between them. This can play a role in the successful initiation of detonations or fast flames. Previous experiments have shown that the transient plasma initiator has an electrical conversion efficiency greater than 50%. In the current experiments, 4.5 J stored in the primary capacitor of the transient plasma initiator was converted to 3.77 J measured at the discharge output. The electrical conversion efficiency is 84%. The spark plug has a 19% electrical conversion efficiency. This is calculated by measuring the charged primary capacitor energy at 0.25 J and dividing it into the output energy measured across the spark gap which is 46 mJ.

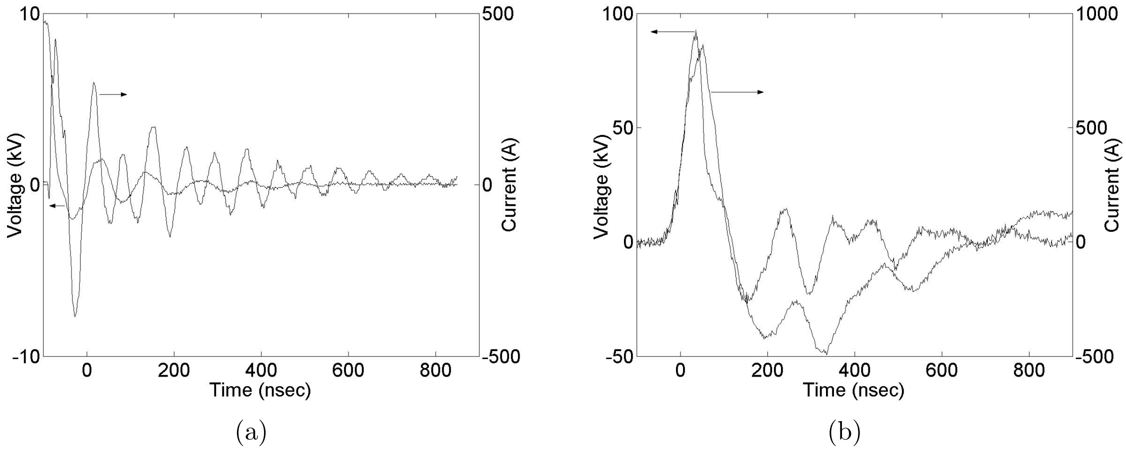


Figure 3. A plot showing the discharge voltage and current versus time for the spark plug (a) and the pulsed corona initiator (b).

A sequence of chemiluminescence images is shown in Fig. 4. The images depict the plasma initiation process of a methane-air mixture with an equivalence ratio of 0.7. This experiment was carried out at 1 atm initial pressure and 298 K initial temperature. A Panasonic AG-190 camera with a 0.0166 s exposure time and a 0.033 s inter-framing time was used. The sequence of images was thresholded and edge detected to locate the edge of the combustion front. The combustion front was determined to propagate radially from the axis to the walls of the initiator chamber with a mean radial velocity of 0.61 m/s ±0.08 m/s.

A laminar burning velocity of 10 cm/s was obtained experimentally[10] for a methane-air combustible mixture at the same initial conditions as in Fig. 4. Using the conservation of mass and the boundary condition that the products of combustion are stationary,[11] a flame speed of 0.62 m/s was calculated and is close to a flame speed of 0.61 m/s measured in the present experiments. The burning velocity is defined as the velocity at which the combustion front propagates with respect to the velocity of unburned reactants. The flame speed is the speed at which the flame propagates in the laboratory frame.

The above calculation shows that an estimate of the flame speed can be obtained from laminar burning velocity data. The sequence of images in Fig. 4 indicates that the transient plasma initiator initiates a combustion wave that propagates radially outward from the center electrode as opposed to a spacially uniform reaction with no visible combustion wave. A characteristic time of propagation may be defined by dividing the tube radius by the computed propagation velocity. The propagation time is a measure of the duration of the combustion process.

The ignition delay time is plotted in Fig. 5a against % N_2 dilution for the various ignition configurations. The ignition delay time, defined as the time from spark or corona discharge till the first pressure transducer, reaches 10% of its maximum value. The figure illustrates that the corona discharge device has roughly a factor of five decrease in the ignition delay time. This persists through the range of nitrogen dilution and ignition configurations tested. The factor of five decrease in ignition time has been previously reported in dynamic fill systems.[5]

The gain in ignition time, although important for the practical operation of a PDE, is highly geometry-dependent. In the current experiments, the spark plug was mounted on the initiator flange and had to combust the entire plasma initiator section before it entered the test section where the first pressure trans-

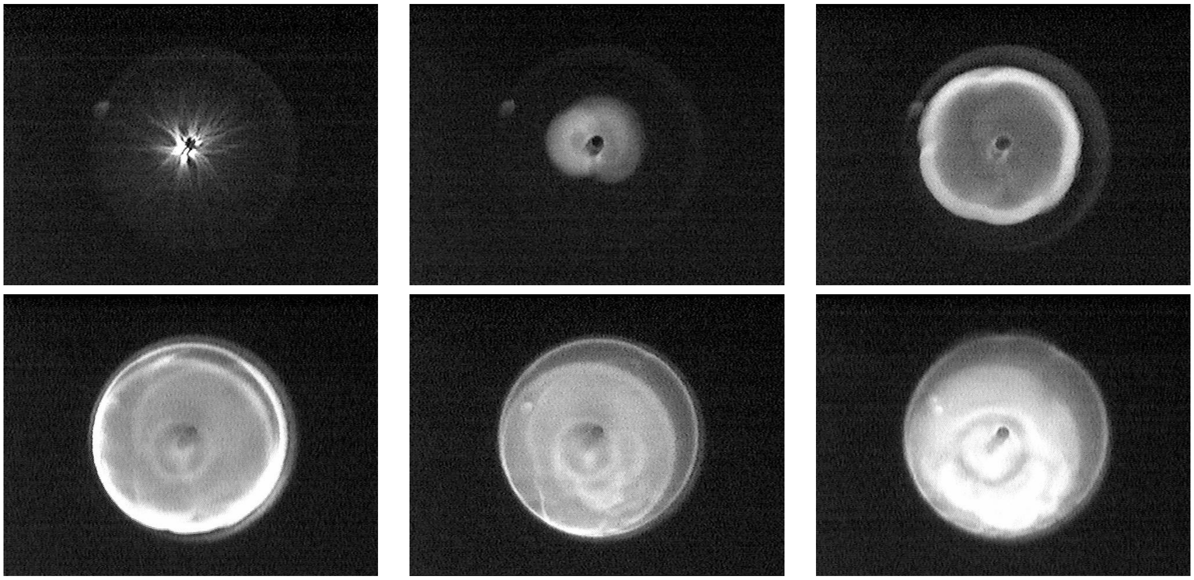
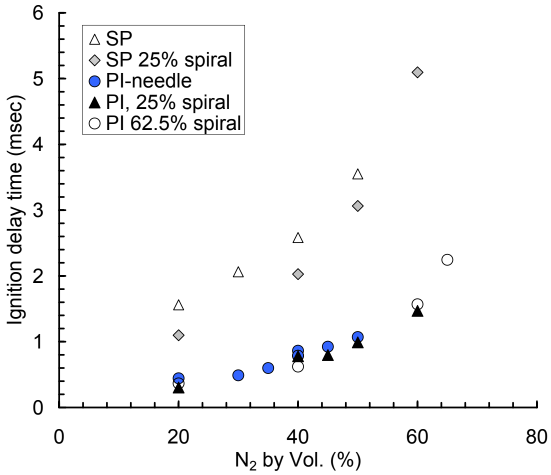


Figure 4. A sequence of chemiluminescence pictures, looking axially down the tube, showing the initiation of a combustion front. The mixture is methane-air with an equivalence ratio of 0.7 at standard temperature and pressure.

ducer was located. This lengthened the ignition delay time compared to the pulsed corona discharge which more readily ignited the entire initiator section volume. It would be more appropriate to compare the pulsed corona ignition delay times to those of a spark plug mounted at the entrance of the test section. Previous work[4] has shown that deflagration to detonation (DDT) times for systems with a spark plug mounted at the entrance of the test section resulted in times closer to the ignition delay times reported for the pulsed corona initiator. Figure 5b shows the results of this comparison. The DDT times lie in between the plasma initiator and the spark plug times. For clarity, all the spark plug data points and the plasma initiator data points from Fig. 5a have been clumped together into two respective groups. The meaning of ignition delay time and DDT time are quite different. The DDT time is the time it takes to record the first detonation observation. The ignition time is the time needed until any disturbance reaches the first pressure transducer. These disturbances are typically detonations or shock waves. The DDT time equals the induction time only if a detonation wave is observed at the first pressure transducer. Therefore, the ignition delay time is a lower bound of the DDT time.

In cases where there was no detonation initiation in the initiator section, shock waves would be the first event observed by the pressure transducers in the test section. To help illustrate this point, Figs 6a,c show examples of a shock wave propagating from the initiator section into the test section. The plots show three pressure traces all with the same scale. The ordinate is with respect to the first pressure trace with each subsequent pressure trace translated vertically in increments of 0.5 MPa. The shock wave is propagating at 500 m/s and 633 m/s between the first and second set of pressure transducers, respectively (Fig. 6a). Consequently, the shock wave is propagating at 633 m/s and 593 m/s between the first and second set of pressure transducers, respectively (Fig. 6c). The plasma initiator produces a slightly stronger shock wave than the spark plug initiator. This is visible from the slightly higher post-shock pressures.

The Mach number of the shock waves was observed to be roughly equal to two. Figure 7 plots the shock Mach number versus β. The experimental Mach numbers are compared to incident Mach numbers calculated using the shock tube equations.[12] The methodology of the shock tube calculations considers an unreacted mixture in the test section. The initiator section initially contains a high-pressure and temperature volume of



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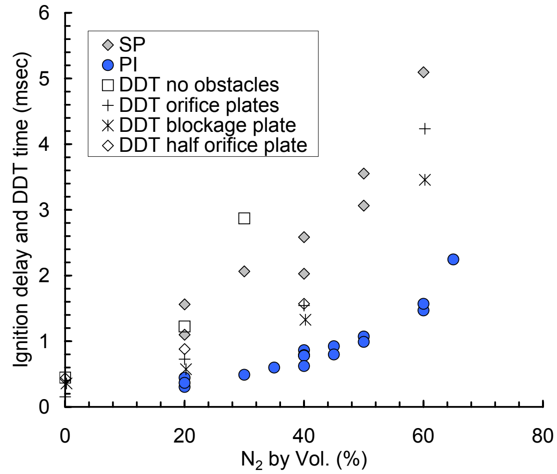


(b)

Figure 5. (a) Ignition delay versus % N_2 dilution for the various ignition configurations. (b) Ignition delay and DDT time versus % N_2 dilution for the various ignition configurations. All data in (b) other than SP and PI are from Cooper et al.[4]

gas equal to the constant-volume explosion conditions of the mixture. The two mixtures are kept separated by a diaphragm. To determine the Mach number, the diaphragm is instantaneously removed and the system is allowed to evolve. Shock and expansion waves emerge to adjust the flow conditions. The initial conditions for the shock tube calculations were performed by computing the constant-volume explosion pressure of the reactants using the STANJAN equilibrium code.[13] The data shown in Fig. 7 is only for smooth tube experiments. The presence of obstacles in the test section results in decreased shock wave velocities. Figure 7 shows agreement between the measured shock velocities and the calculated ones.

As a means of comparison, Figs. 6b,d are pressure versus time plots of a detonation wave propagating from the initiation section to the test section. The ordinate is with respect to the first pressure trace with each subsequent pressure trace translated vertically in increments of 3 MPa. The measured detonation velocity for this experiment was 2270 m/s (Fig. 6b) and 2316 m/s (Fig. 6d) compared to a computed value of 2258 m/s. Notice that the ignition delay times for the plasma initiator cases are less than the corresponding spark plug times.

B. Comparison of Impulse

A plot of the experimentally determined specific impulse (based on the mixture mass) is shown in Fig. 8a. The specific impulse ranges from 20 s to 160 s depending on the specific mixture composition and initiator-obstacle configuration. It is observed that at a given nitrogen dilution, the impulse decreases with the increasing blockage of obstacles. This is due to increased drag.

The dramatic drop off in impulse as the nitrogen dilution is increased is a result of a failure to transition to detonation for these mixtures. The solid curve is the impulse predicted[15,16] for an ideal detonation. Without the use of obstacles, combustion initiated by the corona discharge can transition to detonation for mixtures with up to 45% nitrogen dilution. A spark plug with no obstacles can initiate combustion that will transition to detonation in mixtures with up to 40% nitrogen dilution. Thus, corona discharge is slightly more effective than a standard internal combustion engine spark plug initiating combustion that will transition to detonation. In all cases, the use of turbulence-generating obstacles significantly improved the effectiveness of

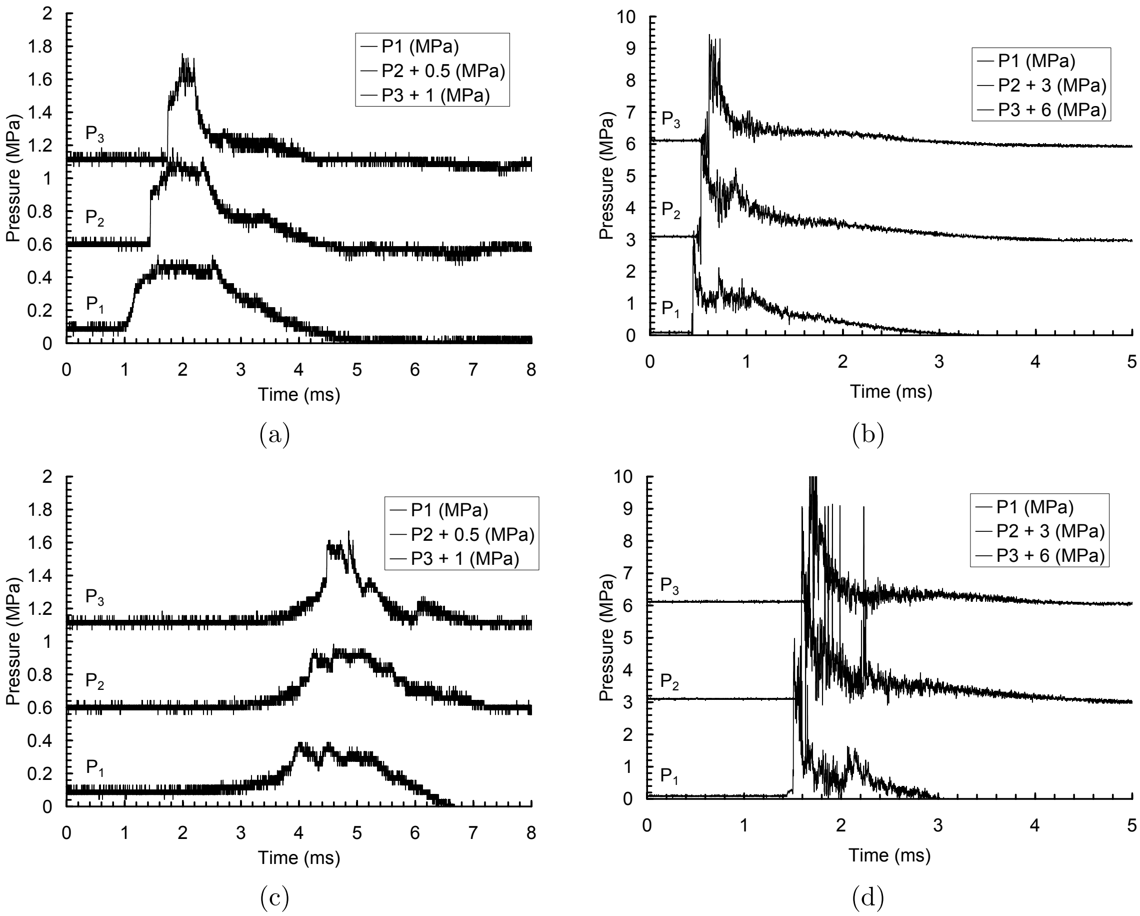


Figure 6. (a) Pressure versus time plot of a shock wave propagating in the test section; (a) plasma initiator, (c) spark plug. Pressure versus time plot of a detonation wave propagating in the test section; (b) plasma initiator, (d) spark plug. The initial mixture composition for all cases was stoichiometric ethylene-oxygen at 1 atm with 20% N_2 dilution for (b) & (d) and 50% N_2 dilution for (a) & (c) .

detonation initiation as has been found previously.[17] Detonations, with the use of obstacles, were observed up to 65% N_2 dilution which occurs in both initiation systems. The corona discharge is effective in achieving very rapid combustion of the region near the electrodes resulting in small ignition delay times. Additional means appear to be needed to accelerate the resulting flame to a detonation for mixtures with greater than 40% nitrogen.

Figure 8b is a specific impulse versus % N_2 plot comparing detonation initiation by means of a turbulent jet.[14] The turbulent jet was created by combustion of a mixture in a 70 cm^3 chamber connected to the detonation tube via an orifice. The data from the turbulent jet study can be compared to the current data using Figs. 8a & b. The data indicate that the impulse for smooth tube detonation cases, generated by a turbulent jet, agree with the data in the present study and follow the impulse model curve. Above a 45% N_2 dilution, detonations are no longer initiated without the use of obstacles and, thus, the impulse decreases because the combustible mixture gets convected out of the tube by shock or compression waves generated by the deflagration at the initiation end of the tube.

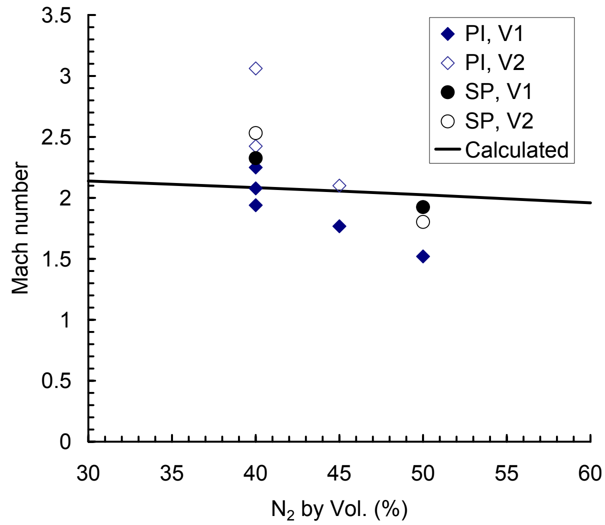


Figure 7. Shock Mach number versus % N_2 by volume for smooth tube experiments. SP = spark plug, PI = plasma initiator, V1 = velocity measurement between transducer 1 and 2, V2 = velocity measurement between transducer 2 and 3.

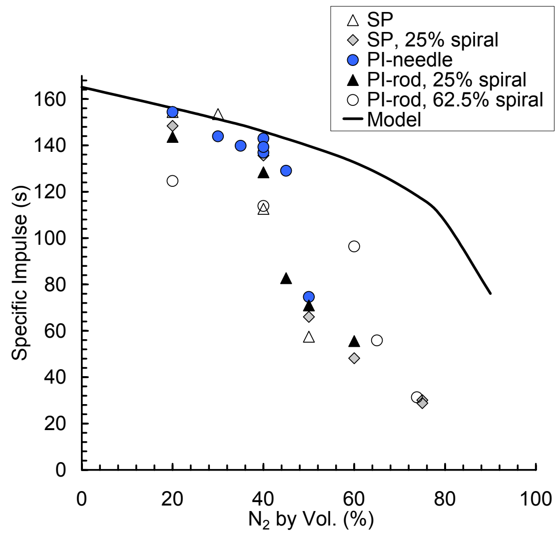
IV. Discussion

A. Pulse Combustion Engine

The transient plasma initiator has relatively low ignition delay times with respect to spark discharge. Consequently, the images in Fig. 4 indicate an azimuthal and axial uniformity of the combustion front. This suggests the idea that the plasma initiator can be an effective quasi-constant-volume explosion generator for volumes on the order of a standard PDE tube. It has been experimentally observed[18] that PDE impulse in a given configuration is maximized if all the combustible mixture is consumed. A numerical analysis[19] over a wide range of parameters indicates that the impulse generated from a constant-volume explosion cycle is within 5% of the detonation impulse for the same initial conditions. In the standard PDE setup with initiation at the thrust wall end, combustion fronts that are not detonations will inevitably push some non-reacted gas out of the system, resulting in a loss of impulse. If the center electrode of the plasma initiator spans the entire length of the PDE, it would be possible to operate this device in a pulsed combustion mode. The combustion wave would need to travel only the radius of the tube instead of its span. This reduction in length, which is a factor of 30 for standard PDE configurations, would enable the combustion to occur at much slower rates while maintaining the same overall burning time. This mode of operation will be referred to as the pulsed combustion engine. A schematic of this configuration is shown in Fig. 9a.

Examining this idea a bit further, consider a detonation tube that has a tube length to radius ratio of 30. For practical purposes, we consider a 1 m long tube with a 6.35 cm diameter. Table 1 lists pertinent values for propane-air and ethylene-air operated as a PDE and as a pulsed combustion engine.

The key values to compare from this table are τ_{s_u} and τ_{ddt}. It is evident that the combustion time is about half the DDT time. This means that one can get increased performance using the plasma initiator (because no obstacles are needed) on roughly half the time scale compared to the DDT experiment. If initiation was not an issue, it is evident that τ_{cj} is an order of magnitude less than τ_{s_u} highlighting the attractiveness of detonation-supported combustion. The limiting process for detonation-based engines is the duration and distance needed for initiating a detonation in air by DDT.



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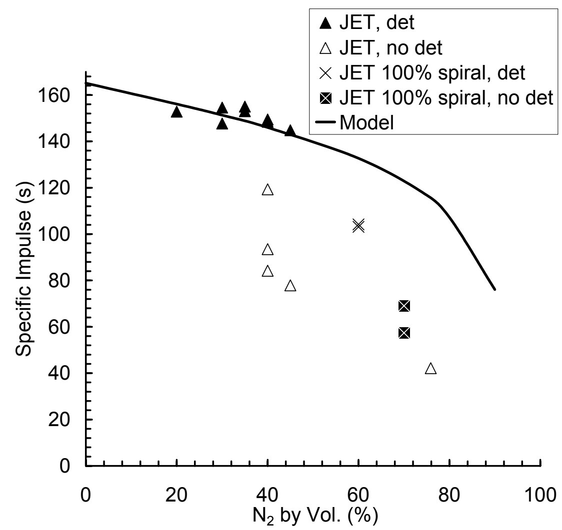

(b)

Figure 8. Specific impulse versus % N_2 dilution of stoichiometric ethylene-oxygen mixtures for various initiator-obstacle configurations. SP = spark plug, PI = plasma initiator. Spiral refers to spiral inserts used to promote transition from deflagration to detonation, det refers to observation of a detonation. The model is described in Wintenberger et al., J. Propulsion Power 19(1), 22-38, 2003. (a) Experiments in current study. (b) Comparison of impulse in current study with jet initiation data (labeled JET) obtained from Lieberman et al.[14]

The analysis discussed above relies on a purely radial flow field. To justify this assumption, the time scale of an expansion fan originating at the tube exit and propagating to the closed end of the tube is considered. This time gives a measure of how long it takes for changes in a flow state at one end of the tube to be known at the other end. Two time scales arise if we consider waves propagating in the reactants and the products of combustion. Using 330 m/s and 890 m/s as the characteristic sound speeds (characteristic of propane and ethylene mixtures) of the non-reacted and burned mixtures respectively, we can calculate expansion times for the 1 m example discussed above. The sound speed values were obtained from constant-volume equilibrium computations using STANJAN. Expansion times of τ_p=1.1 ms and τ_r= 3 ms are calculated for the products and the reactants respectively. Comparing these values to the combustion times of τ_{s_u}=5.8 and 8.8 ms from Table 1 indicates that the expansion wave will reach the entire mixture in the combustion tube during the combustion process and induce an axial velocity component.

Additional reduction in the combustion time τ_{s_u} can be obtained by introducing turbulence, for example, a grid located co-axially around the electrode. Up until now, the combustion time scale has been with respect to a laminar flame. The flame speed can increase by up to a factor of 15 due to turbulence.[22] The resulting turbulent combustion times, τ_v=0.38 and 0.59 ms for ethylene and propane mixtures, are sufficiently small that the simplified radial analysis may be valid. A numerical analysis of the flow field would enable a more quantitative measure of the amount of unburned mixture spilling out of the tube for a finite duration burn.

B. Gradients for Ignition

One way to reduce the detonation initiation time τ_{ddt} is by use of gradients in the initial mixture. Previous experiments[23] have shown that chemical gradients can produce detonations in less than 3 ms. These tests were in acetylene-oxygen mixtures at low pressure, which are more sensitive than the hydrocarbon fuel-air mixtures of interest. The idea of gradient initiation is based on coherently coupling the chemical energy

	C_2H_4-Air	C_3H_8-Air
S_u[10,20] (cm/s)	68	45
E	8.1	8.0
V_f (m/s)	5.5	3.6
V_{cj} (m/s)	1825	1801
τ_{s_u} (ms)	5.8	8.8
τ_{cj} (ms)	0.5	0.6
τ_{ddt}[5,21] (ms)	12.5 $\pm$0.5	23.5 $\pm$0.5

Table 1. Table of characteristic time scales for PDE and pulse combustion engines.

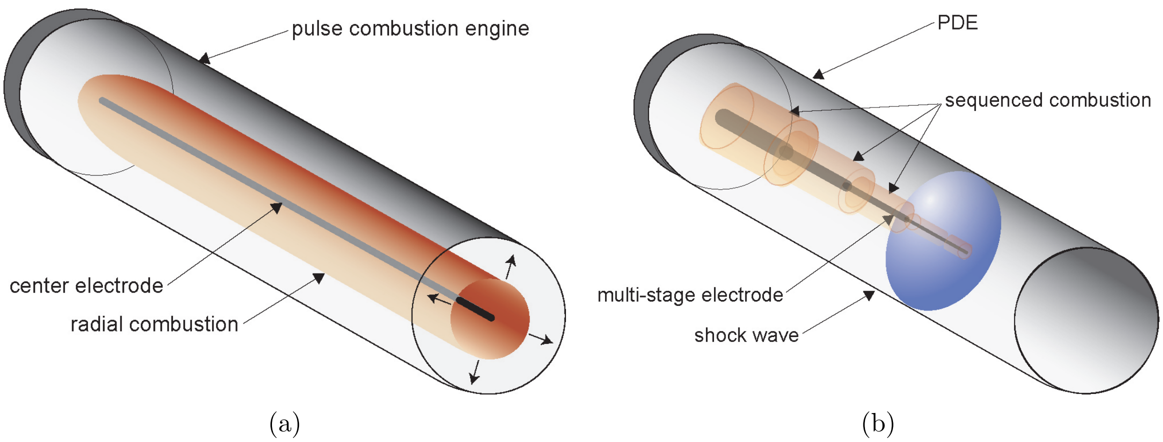

Figure 9. (a) Sketch of a pulse combustion engine configuration. The center electrode spans the length of the tube and initiates a radial combustion wave. (b) Sketch of a PDE using a sequence of independent transient plasma discharges to initiate a detonation.

release with the amplification of a shock wave. This is termed the SWACER mechanism by Lee.[23] Various numerical[24] and asymptotic[25] studies indicate the potential for such a method. Recently, experiments were carried out using an array of spark plugs to promote rapid detonation ignition through the SWACER mechanism.[26] The key to the successful implementation of this mechanism is the precise timing for depositing energy behind the developing shock wave. The plasma initiator might be a good candidate for this task because of its ability to ignite over a larger area than a conventional spark discharge. The proposed experiment, illustrated in Fig. 9b, would be to create a sequence of discharges along the tube axis to produce amplification of the leading shock front.

V. Conclusion

Experiments were carried out to determine the effectiveness of the transient plasma initiator on initiating detonations in stoichiometric ethylene-oxygen systems varying the amount of nitrogen dilution. The results indicate that the plasma initiator can initiate a detonation up to 45% N_2 dilution compared to a spark which is limited to 40% N_2 dilution. By using obstacles to enhance DDT, this limit was raised to 65% N_2 dilution. Thus, detonations are observed at higher amounts of nitrogen dilution, but the impulse is lower for obstacle-laden tubes.

Ignition delay times were measured and found to be a factor of five shorter for the plasma initiator compared to the spark discharge system. This result was expected to be sensitive to the location of the spark plug and the two order of magnitude difference between the electrical energy used in the two systems.

Shock waves were first observed in experiments where detonations were not recorded exiting the initiator section. In smooth tube experiments, the shock waves propagated with a Mach number around two. This has been compared to shock tube calculations based on rapid combustion of the initiator volume and found to be in reasonable agreement.

The combustion process of the plasma initiator, as shown in Fig. 4, was determined to be a radial low-speed combustion flame propagating outward from the electrode located on the tube axis. In our study, the plasma initiator behaves more like a distributed spark source than a volumetrically uniform initiation.

The concept of using the transient plasma initiator in a pulsed combustion mode was introduced and compared to the PDE. Combustion time scales were calculated for stoichiometric propane-air and ethylene-air mixtures in detonation tubes. It was found that the combustion time scales τ_{s_u} (5.8, 8.8 ms) were less than half the τ_{ddt} (12.5, 23.5 ms) indicating that it requires less time to burn a mixture in the slow-combustion mode radially than it does to use the DDT mechanism and initiate a detonation to propagate the length of a tube. The pulsed combustion mode, consequently, does not require the use of obstacles that produce drag in the axial direction which affect the impulse of the device. Blow-down time scales associated with the expansion of the burned products were also calculated and indicate that higher flame speeds associated with turbulent combustion are needed to produce a radially dominant flow in the tube. However, this would be best quantified with more detailed numerical simulations or experiments.

A method for reducing the time required to initiate a detonation with the plasma initiator was proposed. The idea makes use of a sequenced ignition source to create an appropriate energy release gradient.

Acknowledgments

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