Plasma-assisted Deflagration to Detonation Transition of Dimethyl Ether in a Microchannel

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1 Abstract

A plasma microchannel is used to experimentally analyze the effect of plasma on deflagration to detonation transition (DDT) in DME:O_2:Ar mixtures at atmospheric pressure. Nanosecond dielectric barrier discharges, ns-DBDs, are applied across the length of the microchannel before ignition. A high speed camera is used to trace the time histories of flame front position and velocity and to identify the dynamics and onset of DDT. The results show that plasma discharge can nonlinearly affect the onset time and distance of DDT. It is shown that a small number of plasma discharge pulses prior to ignition result in reduced DDT onset time and distance by 60% and 40% when compared to the results without pre-excitation by ns discharges. However, the results also show that an increase of plasma discharge pulses results in an extended DDT onset time and distance of 224% and 94%, respectively. The present experiments demonstrate the ability to control DDT by using non-equilibrium plasma of transversal DBD for applications in advanced propulsion engines.

2 Introduction and Background

Previous studies have shown that ozone can chemically sensitize fuels with and without low temperature chemistry, more dramatically so for fuels with low temperature chemistry. [1,2] Unfortunately however, ozone thermally decomposes at temperatures above 450 K, making it difficult to use directly in practical engines at elevated temperatures. Therefore, it is desirable to develop a non-equilibrium plasma discharge which would generate active radicals to directly initiate and accelerate DDT in-situ. Non-equilibrium plasma creates fast and slow heating of a mixture due to electronic excitation and vibration-rotation energy transfer. Moreover, it generates active species such as atomic oxygen and electronically excited nitrogen and oxygen molecules which can significantly enhance low temperature and high temperature ignition and fuel oxidation and thus enhance combustion processes.[3-7] As such, non-equilibrium plasma has a great potential in the development of next generation propulsion engines such as in pulse detonation engines (PDEs) and rotation detonation engines (RDEs), both of which employ a constant (or decreasing) volume cycle as opposed to a constant pressure cycle which could increase engine efficiency by 30%.[8] However, before plasma discharges can be used in such practical applications, we need to better understand which mechanisms, thermal or non-thermal, have the greatest effect on DDT dynamics.[9]

This study aims to identify the effect of ns-DBD plasma on the dynamics and onset of DDT. For this study, several sequences of a uniform ns DBD plasma are pulsed across a 1 mm tall, 4 mm wide, ~60 cm long combustion channel filled with dimethyl ether/oxygen/argon premixture at an equivalence ratio of 0.7. A high speed camera is used to image the flamefront and traces its propagation position and velocity, as well as to locate the deflagration to detonation transition. The results show that plasma discharges can *both* dramatically increase and decrease onset time and distance of DDT.

3 Experimental Methods

The detonation tube was a channel with a rectangular cross section of 1x4 mm^2 and a length of 600 mm. A dielectric barrier discharge was formed across the channel between copper electrodes isolated from the discharge gap by a Kapton® film. The distance between the electrodes was 1 mm, the width of the electrodes corresponded to the width of the channel (4 mm), and the length of the electrodes was 500 mm. A spark gap was installed at a distance of 50 mm from the edge of the DBD electrodes to initiate a combustion wave in the channel. The channel is filled through a needle feed-through at one end, the opposite side of the channel has a needle feed-through serving as a vent valve. The assembly is clamped together with fasteners through the frame pieces, nylon insulating tubes shield the fasteners.

Figure 1: Image of ns-DBD plasma generated in the cell.

The plasma discharge is generated by a DC high voltage supply and pulser, and is controlled by a signal generator. A trigger initiates a sequence of 10 kV, 10 kHz, 200 ns pulses ahead of ignition, pre-pulses. The timing is highlighted in Figure 2.

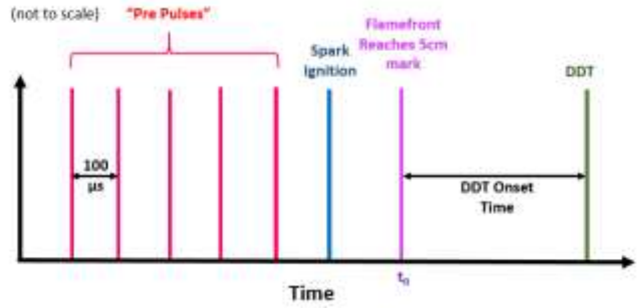

Figure 2: A schematic of the plasma discharge, ignition, and onset of DDT timing sequence.

4 Results and Discussion

For this study, a test case of zero pre-pulses, as well as cases of 10, 15, 20, 30, 50, 100, 200, 500, 1000, 2000, and 5000 pulses ahead of ignition are studied. Two batches (trials of 6) are conducted for the cases with fewer pulses (10-30) and one batch for the higher pulse cases (50-5000). Four batches are conducted for the no-plasma case. These batches are cycled to ensure repeatability. The initial time used in determining the time to onset of DDT is defined as the time at which the flamefront has propagated 5cm and the onset distance is the distance traveled after 5cm to the point of DDT, this is to ensure the results are independent of variations in initial ignition kernel development. The resultant average onset time and distance are plotted in Figure 3. It is seen that the case of 15 pre-pulses provides the strongest enhancement. Onset distance is reduced from an average of 19cm to 12cm, a 40% reduction. Onset time is reduced from 146µs to 64µs, a 60% reduction. In the trials with a higher number of plasma pulses we start to see the DDT onset time and distances extended by up to 224% and 94%.

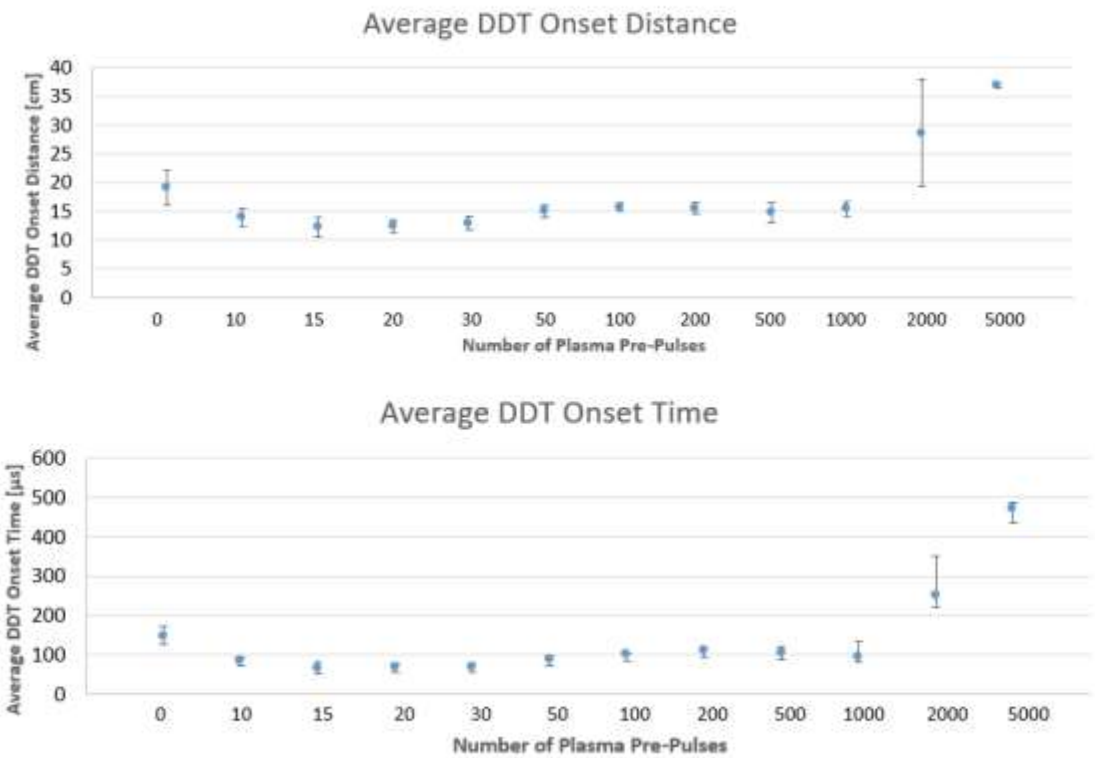

Figure 3: Average DDT onset distance and time with error bars for standard deviation.

To better understand these results, it is helpful to examine the velocities of the flamefronts over time for the various plasma conditions, Figure 4. In the control case, no plasma pulses, two distinct acceleration events occur, one around 100 µs and one around 160 µs. These are the two stages of a multi-stage ignition. The first stage is due to the presence of low temperature chemistry, and the second is the high temperature auto-ignition and DDT where we see a steep overdriven velocity before the front settles down to Chapman-Jouguet velocity. When 15 pulses are applied, we see in the most efficient trials, that the high temperature chemistry is accelerated such that the second acceleration proceeds directly from the peak of the first, and any negative acceleration is eliminated. When 5000 pulses are applied, we instead see the second acceleration event is greatly delayed, and the negative acceleration following the first flamefront acceleration in increased.

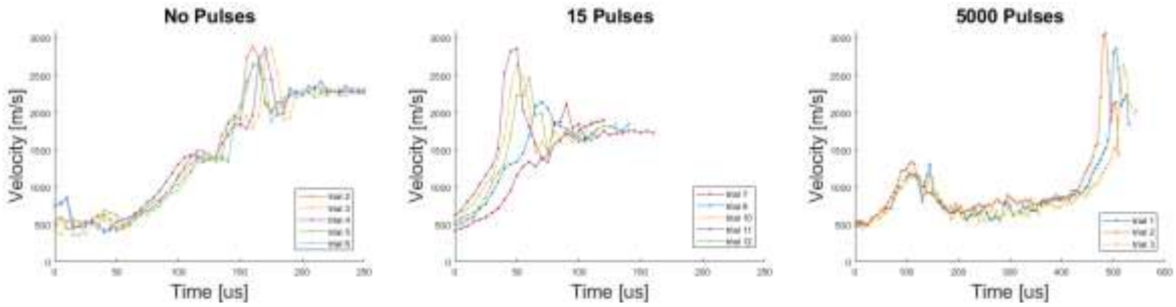

Figure 4: Flamefront velocity as a function of time for the control case, no plasma pulses, as well as the cases resulting in the greatest reduction and increase in DDT onset distance and time, 15 pulses and 5000 pulses respectively.

When considering the two distinct phases of the plasma ignition process, an initial non-equilibrium plasma phase, during which electrons transfer energy into electronically excited species that accelerate reaction rates, and a spatially distributed thermal phase, that produces exothermic fuel oxidation reactions that result in ignition, interpreting these results becomes clear.[10] In the cases with fewer pulses we see positive effects from both the excitation phase and the thermal phase. The case of 15 pulses best leverages the timing of these benefits. In the cases with a higher number of pulses, the timing is such that the species have relaxed, eliminating the accelerative effects of the excitation phase, and the thermal phase has advanced too far. Rather than strengthen ignition, the oxidation reactions have completed and the partially reacted premixture has returned to thermal equilibrium, now less reactive than its initial state. A higher number of pulses eventually fully inhibits DDT. The nonlinear plasma enhancement of DDT is a direct result of these balances, and can ultimately be leveraged to control DDT onset time and position.

5 Conclusions

DDT experiments in DME/O_2/Ar mixture of atmospheric pressure have been carried out, demonstrating that transversal ns-DBD can chemically sensitize the DME mixture and accelerate the DDT transition both in space and time. In cases with a higher number of pulses we see the transitions, instead, delayed – suggesting that the benefits of the excited species and radicals are outweighed by the plasma assisted fuel oxidation of the premixture and decrease of the chemical energy of the mixture. The ability to control DDT with plasmas is promising for the development of next generation rocket engines, and opens the opportunity to demonstrate further improvement in lean burn flame stability, low temperature fuel oxidation and processing, as well as in emission reduction.

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