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Pressure Scaling Effects on Ignition and Detonation Initiation in a Pulse Detonation Engine

Andrew Naples[1] and Sheng-Tao John Yu[2]
The Ohio State University, Columbus, OH 43210

John Hoke[3]
Innovative Scientific Solutions Inc., Dayton, OH 45440

Kenneth Busby[4]
Universal Technology Corporation, Dayton, OH 45432

Frederick Schauer[5]
Propulsion Directorate, Wright-Patterson AFB, OH 45433

An experimental study was done to examine the effects of elevated initial tube pressure in the Pulse Detonation Engine (PDE). Measured parameters were the ignition time, deflagration to detonation transition (DDT) run-up distance, DDT times, and Chapman-Jouguet (C-J) velocity. Mixed with air, three fuels, i.e., aviation gasoline, ethylene, and hydrogen, were tested at various initial pressures and equivalence ratios. An aftermarket automotive ignition system was employed, along with two plasma ignition systems to quantify the benefits of each. Measured results show a reduction in the ignition time of roughly 50% and in the DDT distance of roughly 30%, for all three fuels at an initial tube pressure of 3 atmospheres. With atmospheric initial tube pressure, the transient plasma ignition system yielded the shortest ignition times, followed by the thermal plasma ignition system, and lastly the aftermarket automotive ignition system. At roughly 2 atmospheres of initial pressure the thermal plasma ignition system showed no benefit over the aftermarket automotive ignition system. C-J wave speeds have shown to increase with elevated initial pressure, and agree with numerical results. In addition to the experimental results, a brief Chemkin analysis was done to model the aftermarket automotive ignition system to estimate ignition times of the mixtures at pressures that were not tested.

I. Introduction

PDEs have been heavily researched in recent years due to promises of high efficiency, low emissions, scalability, and simplicity[1]. For these advantages to be realized, detonation must be achieved quickly and reliably. The research presented here provides experimental results that characterize the effect of initial detonation tube pressure on mixture ignition and detonation initiation. The data set constructed in this study yields measured results to be used by detonation researchers.

Some detonation tube initial pressure research has already been completed. The effects of converging nozzles on the PDE performance with hydrogen/air mixtures have been examined [2-4]. Knick found that increasing pressure with converging nozzles reduced ignition time by 20% at 160kPa. Results show smaller ignition time decreases at pressures above 160kPa pressure, and diminishing decrease in ignition time as ignition delay increases. Other results from Knick’s study show increasing DDT times and decreasing detonation initiation time as initial tube pressure increases.

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[1] Master’s student, Currently Research Engineer at ISSI, AIAA Member
[2] Professor, Mechanical Engineering, AIAA Member
[3] Senior Engineer, 2766 Indian Ripple Rd., Dayton, OH 45440, AIAA Senior Member
[4] Research Scientist, 1270 N. Fairfield Rd., Dayton, OH 45432, Stationed at the Aerospace Propulsion Division, WPAFB, OH 45433, AIAA Member
[5] Research Engineer, 1790 Loop Rd., Dayton, OH

Other related research was conducted for moving hydrogen/air mixtures at elevated initial tube pressures and temperatures[5]. Chapin et al examined the effect of initial pressure, temperature, and flow velocity on the DDT time and length. Increasing initial pressure or flow velocity proved to decrease the total detonation time, while an increase in any of the three variables decreased the detonation distance. Results show that flow velocity has the largest effect on total detonation initiation time followed by initial pressure. Initial temperature showed no substantial effect on the total detonation initiation time. Temperature had the largest effect on detonation initiation distance, followed by flow velocity and lastly, initial pressure.

Another area of interest in the current research is using plasma ignition systems at elevated initial tube pressures. Plasma ignition systems have been heavily researched in the PDE at atmospheric initial tube pressure[6-8]. A comparative analysis of published results by Cathey et al[8] shows that transient plasma ignition systems have the capability to reduce ignition time by a factor of 2, and up to a factor of 9 over lower energy thermal ignition systems. Improvements have also been reported in the DDT time when using a transient plasma ignition system.

II. Experimental Setup

The PDE used for this research is located at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB). The PDE is comprised of a General Motors Quad-4 Dual Overhead Cam (DOHC) cylinder head, with detonation tubes replacing the internal combustion engine cylinders. Various support systems supply the research PDE with air flow, fuel flow, valve motions, and other essential support for operation. The engine and its facilities have been used for various published results and are described in detail elsewhere[1].

The setup used in the experiments presented here involved two detonation tubes. A 24 gallon tank was attached to the end of each of the 2.067” internal diameter, 82” long detonation tubes. On the other end of each tank has a 0.80” diameter orifice that restricted air flow out of the system, elevating the initial pressure in the tank and detonation tube. Inside each tube was a Schelkin spiral, used to accelerate the deflagration to detonation transition process. The spiral length was 18” for hydrogen testing, 36” for ethylene testing, and 48” for aviation gasoline testing. The setup of one tube is shown in Figure 1.

Though two detonation tubes were used during testing, data was only taken from one tube. The tube from which results were tabulated is outfitted as shown in Figure 1. The second tube provided a balancing effect to the system by reducing the mass flow stoppage time, which reduces the equivalence ratio oscillation. Thus, there was no need for sensors on the second tube, and the setup of this secondary tube is similar to Figure 1, without the ion probes and pressure transducer.

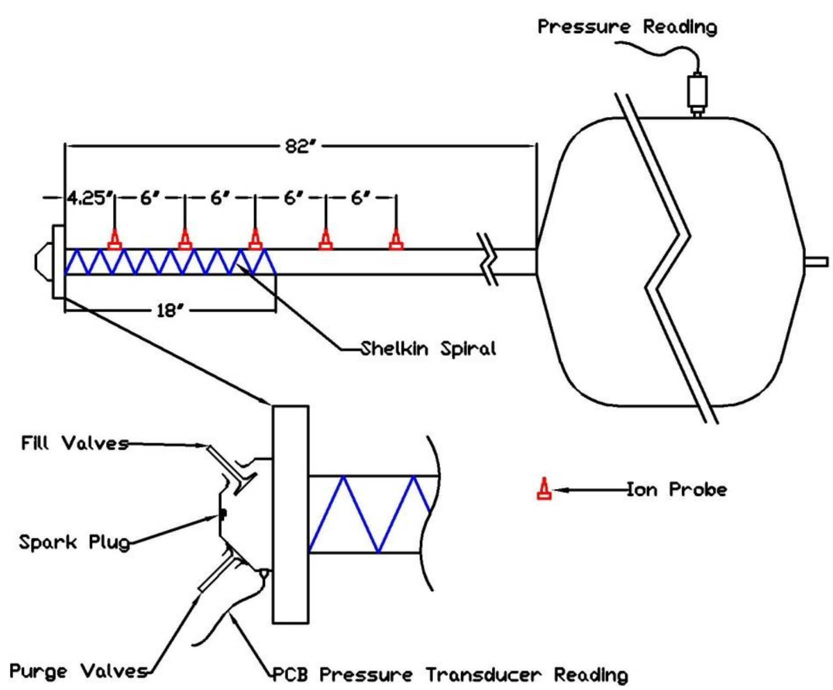

Figure 1: Schematic of detonation tube setup for elevated initial pressure testing.

The tanks in this setup increase the mass of air that is pressurized. This increase in mass provides a more gradual decline in tube pressure once mass flow into the tube stops and the pressurized mixture begins exhausting through the restricting orifice. Pressure was varied with this system by changing the mass flow rates into the detonation tubes. The higher mass flow rate trying to exhaust through the restricting orifice causes higher initial detonation tube pressures. Changing the fill and purge fractions or the engine frequency of the PDE cycle changes the flow rates into the tubes, allowing the flow to be increased or decreased. Each of these methods allowed modification to the flow rates without modifying the setup or equivalence ratio, and were capabilities of the facilities already in place.

Three ignition systems were examined for the current research. First was an aftermarket automotive ignition system built by MSD ignition (PN6215 DIS-4). This ignition system, termed the MSD ignition system for the remainder of the paper, provides three rapid pulses each PDE cycle. The exciter energizes to 115mJ, but only 3mJ of that energy is discharged in the spark, over a time lapse of 50 microseconds per discharge[6]. The other two ignition systems employed were plasma ignition systems built at AFRL. The first ignition system has an exciter energy of 0.85J and is termed the thermal plasma ignition system for the remainder of this paper. This provides a discharge of 0.4-0.55J over a 500 microsecond time lapse (baseline to baseline). The second ignition system an exciter energy of 0.95J and is termed the transient plasma ignition system for the remainder of this paper. This provides a discharge of 0.25-0.3J over a time lapse of 50-75 nanoseconds (baseline to baseline). Both plasma systems used a non-resistive Autolite AR3934 racing spark plug, while the MSD ignition system used a resistive Autolite 4302 spark plug.

III. Definition of Measured Variables

The PDE works on a three-phase (fill, fire, and purge) cycle. The fill phase involves injecting the detonation tube with a detonable mixture. The fire phase includes establishing a detonation, allowing the detonation to propagate through the detonable mixture, and then exhausting of the hot combustion products, producing the bulk of the PDE thrust. Lastly, the purge phase is fresh air flow to cool off the detonation tube and any internal components, while creating a barrier between the hot combustion products of the fire phase and the fresh charge of the next fill phase.

The current research concentrates on the fire phase of the PDE cycle. Figure 2 shows a timeline of the fire phase in the PDE. The ignition delay is a user specified time that represents time from the close of fill valves to spark discharge. The ignition time is the time from spark discharge to the formation of a deflagration flame. The DDT time is the time needed for the combustion waveform to transition to a detonation, and the wave propagation and exhausting time is the time needed for the detonation wave to traverse the tube and the hot combustion products to exhaust, creating thrust. The ignition time and DDT time were examined in this research, along with the DDT run-up distance, or DDT distance. This is the length of tube needed for the initial deflagration flame to accelerate to a detonation wave.

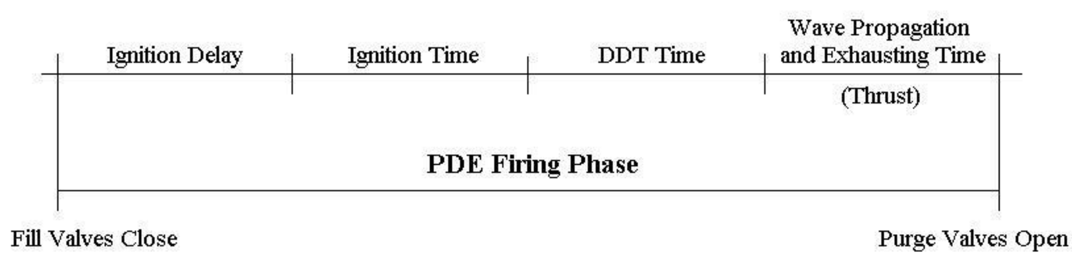

Figure 2: Timeline of the fire phase portion of the PDE cycle.

IV. Measurement Methods and Data Analysis

The ignition time was measured using a PCB pressure transducer. This probe was located at the closed end of the detonation tube, and provided a dynamic pressure transducer trace. The ignition time is recorded as the time when the dynamic pressure transducer trace first reaches a 5V/s slope. This method of ignition time measurement was previously tested, and confirmed to yield ignition times 10-15% faster than OH radical imaging[9].

Wave speeds were measured using ion probes. The ion probe system used was developed for the PDE by air force researchers[10]. The ion probe is essentially two leads that have a voltage potential across them. The voltage between the two leads is shorted by the ions of a combustion wave as it reaches the probe's location. A drop in the voltage signal of the ion probe represents when a combustion wave reaches the ion probe's location, providing the arrival time of a combustion wave. The locations of the ion probes are also known. Thus, the wave speed between two ion probes can be calculated by the change in ion probe location, divided by the change in ion probe detection time. The C-J velocities were found by detecting multiple consecutive wave speeds down the length of the detonation tube. Once the same wave speed was detected for two consecutive intervals, it is taken as the C-J speed.

To calculate DDT distance, multiple wave speeds were measured down the length of the detonation tube. Ion probes were placed such that a wave speed was measured before and after the onset of detonation. The location where a wave speed is achieved was assumed to be the center of the ion probe interval over which the wave speed was calculated. Using the wave speed that was measured before the onset of detonation and the wave speed measured just after the onset of detonation, linear interpolation yields where the C-J velocity is first achieved. The distance from the spark plug to this location is the DDT distance.

Calculating the DDT time was found in a similar way. The time a wave speed is achieved is defined as the average time of the two ion probes between which the wave speed is calculated. Once again, linearly interpolating between wave speeds that are higher and lower than the C-J speed, yields the time when a detonation is first achieved. The ion probe times are defined starting from the discharge of the spark, thus the ignition time is subtracted from the time where a detonation is first achieved, yielding the DDT time.

To extract the quantities of interest, an in-house developed computer program was used. This program applies a standard way of extracting results from the sensors, and greatly reduces data analysis time. A typical data set included 5 ion probes, dynamic head pressure, spark signal, and snubbed tank pressure. Each sample was taken for 0.5 seconds, and sampled at a rate of 1MHz, yielding accuracy to the microsecond. The program first filters the dynamic pressure signal with a Savitsky-Golay filter[11]. The program then takes a 600 point window and finds the slope via linear regression. The window moves along the dynamic pressure trace, 1 point at a time, until the regression slope reaches 5V/s. Once a window with a 5V/s slope is found, the center of this window is declared the ignition time. The program will calculate the ignition time for each spark discharge recorded. Moving forward from the ignition time, the program averages the first 500 points of the ion probe trace. The program then follows the ion probe trace looking for 500 consecutive points that fall below the averaged trace value. The first of these 500 points is declared the ion probe time, and is given with respect to the spark discharge.

Once all of the ignition times and ion probes times are found by the in-house program, the values are put into an excel spreadsheet where the calculations described above are carried out. Values are collected from the excel spreadsheet and averaged to yield one data point, which is plotted in the results section. The standard deviation of the data point is used in the error analysis, to formulate the error bars on the plots in the results section of this paper.

V. Error analysis

The total uncertainty in the measurement results was found using the methods outlined by Coleman[12]. Total uncertainty is the square root of the sum of squares of the random uncertainty and systematic uncertainty. Random uncertainty is based on scatter of the measurements. The random uncertainty was determined using a normal distribution of the data collected for each data point. A 95% confidence interval was determined as the random uncertainty, and is equivalent to twice the standard deviation of the data measured. Systematic uncertainty is dependent on the limitations of sensors and control systems. Errors in the sensors are propagated through calculation steps, to arrive at the systematic error in the measurement. Systematic uncertainties in the measurements of this research are presented in Table 1. The error bars presented in results represent the total uncertainty of the data points.

Table 1: Systematic uncertainties of results

Result	Systematic Uncertainty
Ignition Time	
Hydrogen	$\pm 94 \mu s$
Ethylene	$\pm 158 \mu s$
Aviation Gasoline	$\pm 354 \mu s$
DDT Time	
Hydrogen	$\pm 113 \mu s$
Ethylene	$\pm 170 \mu s$
Aviation Gasoline	$\pm 360 \mu s$
DDT Distance	$\pm 0.105 m (4.126")$
Equivalence Ratio	
Hydrogen	± 0.017
Ethylene	± 0.017
Aviation Gasoline	± 0.015
Initial Pressure	$\pm 4.8 kPa (0.70 psi)$

VI. Chemkin Analysis

Chemkin was used to model the finite rate kinetics of the combustion initiation, to yield more understanding into the behavior of the spark. A 0-D batch reactor model was used to model the spark-affected volume of the mixture. A combination of initial temperature and initial OH radical species concentration was used to model the mixture just after spark discharge. The Chemkin software outputs various traces such as species concentrations and temperatures. Since the method used to measure ignition time was verified by OH radical imaging, the ignition time is defined as the inflection point of the OH species mole fraction.

In order to converge on one solution while varying two parameters, the Chemkin analysis was used to match the curve of the experimental data. The temperature and OH species initial concentration were varied until the atmospheric pressure ignition time for the stoichiometric equivalence ratio was matched. Then using the same temperature and OH initial species, the results were found for pressures up through the testing regime. The two parameters were varied until the curve fit the data well; then the temperature and OH-species initial concentration combination were recorded as constituents of the state of the spark-affected volume just after spark discharge.

Once the temperature and OH species concentration were found for the stoichiometric equivalence ratio, the same temperature was used for all other calculations of ignition times. The OH species initial concentration was varied to match the atmospheric pressure point of each of the other equivalence ratios. This method matched well at all equivalence ratios, including rich equivalence ratios at elevated initial pressures, where initial conditions were not varied to directly have results match the data.

VII. Results and Discussion

Ignition Time

The relationship between ignition time and initial pressure was extensively studied. Figure 3 shows a reduction in ignition time as pressure increases, across equivalence ratios 1.0-1.3, for the aviation gasoline/air mixture. This data was taken using MSD ignition system. Also shown are the results from the Chemkin analysis, which agree well, as expected based on the iteration method explained before. The error bars from the atmospheric condition do not overlap the error bars from either of the higher pressure points, suggesting a definitive reduction in ignition time.

The ignition time also varies with ignition systems. Figure 4 shows ignition times were minimum when the transient plasma ignition system was employed, and maximum when the MSD ignition system was employed at atmospheric initial pressure. Elevated pressure testing was done for the thermal plasma ignition system, revealing a decrease with elevating initial pressure. However, as initial pressure increased, the thermal plasma ignition system showed little improvement over the MSD ignition system. Figure 5 shows a summary of all three ignition systems at multiple initial pressures. The percentage reduction is calculated with respect to ignition time at atmospheric initial pressure, with the MSD ignition system employed.

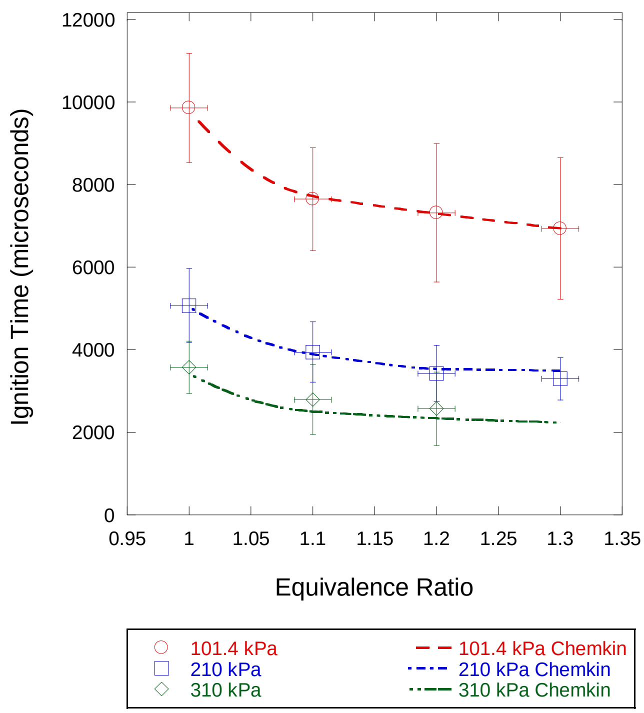

Figure 3: The ignition time as a function of initial tube pressure and equivalence ratio for the aviation gasoline/air mixture.

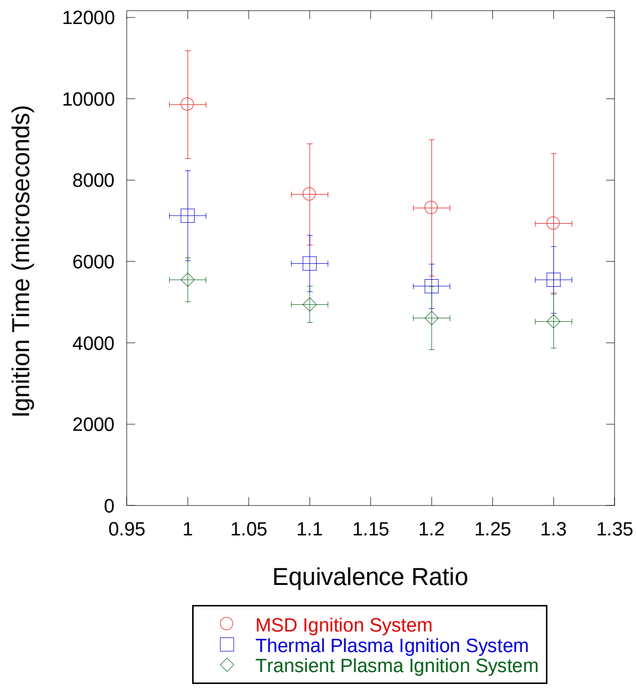

Figure 4: Ignition time as a function of equivalence ratio, for the MSD, thermal plasma, and transient plasma ignition systems. The initial tube pressure was atmospheric.

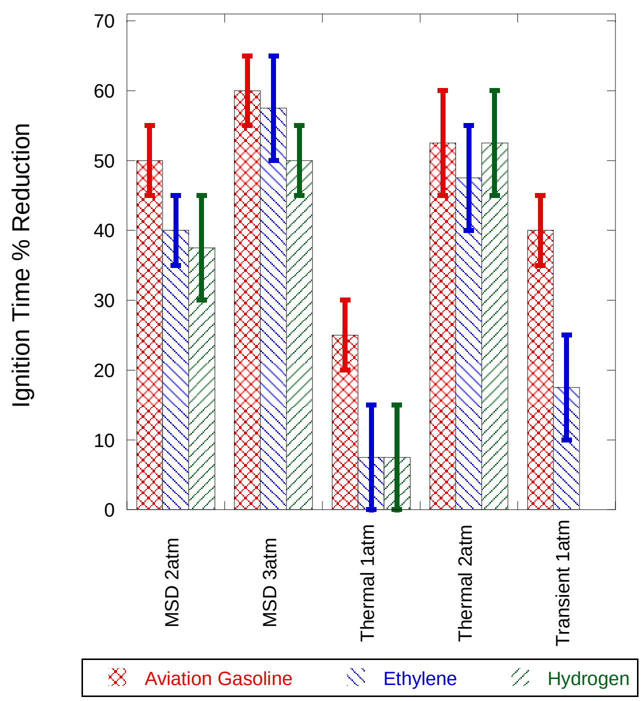

Figure 5: Summary of ignition time reductions. Percentages are with respect to the MSD system ignition times at 1 atm. Results from all equivalence ratios are included.

DDT Distance

The DDT distance reduced as initial pressure increased. Figure 6 shows the DDT distance for the aviation gasoline/air mixture, with the MSD ignition system employed. Ignition systems had no effect on DDT measurements and the repeated measurements are not presented here. Ethylene/air and hydrogen/air mixtures proved to follow a similar trend with respect to initial pressure. The reduction in DDT distance varied amongst the different equivalence ratio and mixture combinations, but a minimum reduction of 15% and a maximum reduction of 40% was realized at 3 atmospheres of initial pressure for all combinations tested.

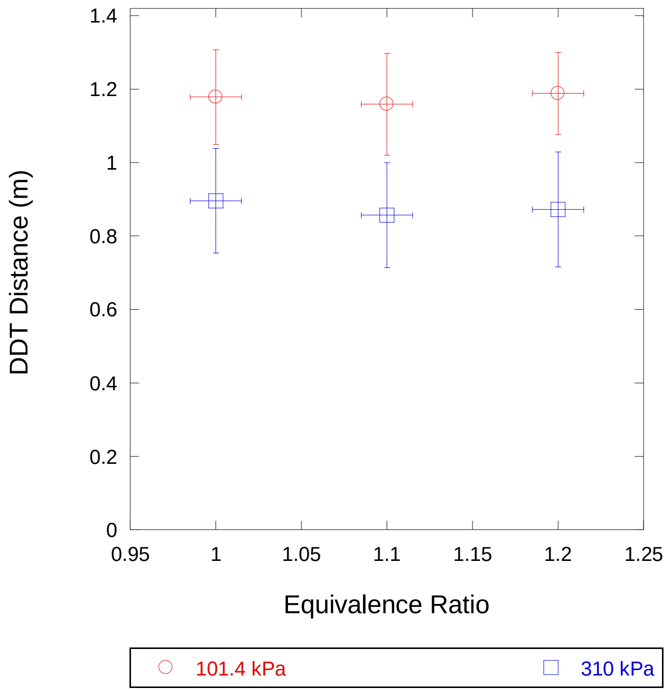

Figure 6: The DDT distance as a function of initial pressure and equivalence ratio for the aviation gasoline/air mixture.

C-J Velocity

The C-J velocities were also calculated for all three fuels when combined with air. Figure 7 shows the variation of the C-J velocity with equivalence ratio and initial detonation tube pressure for the hydrogen/air mixture. The data shows a trend similar to that found numerically and reported in the detonation database[13]. The higher initial pressure C-J velocities, however, correspond with the calculated atmospheric initial pressure results better than the measured results at atmospheric initial pressure. A similar result is found in Figure 8 for the ethylene/air mixture.

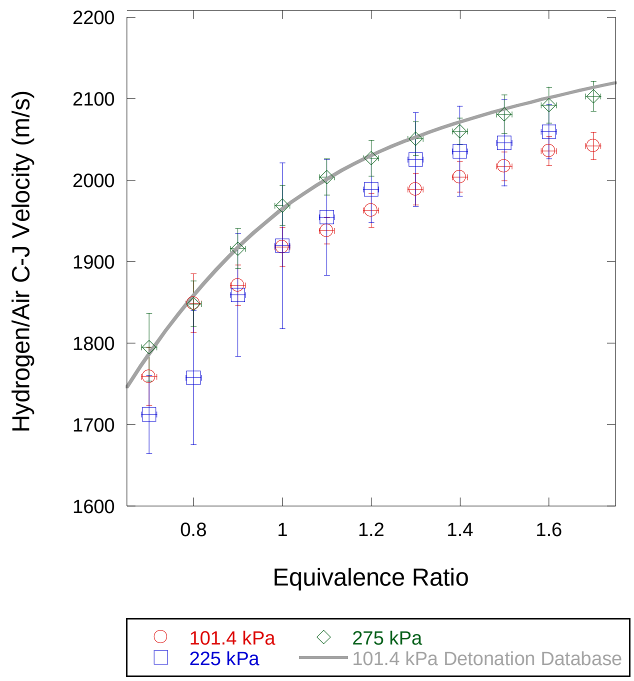

Figure 7: C-J velocity of the hydrogen/air mixture as a function of initial pressure and equivalence ratio.

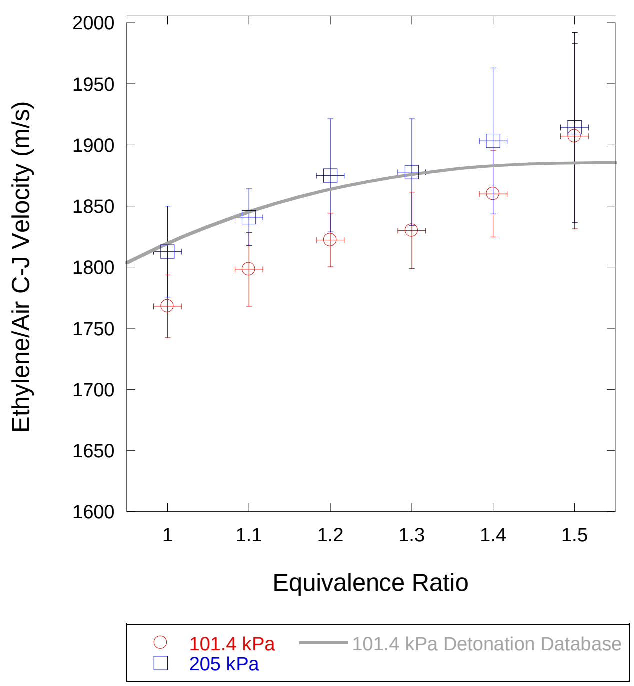

Figure 8: The C-J speeds of the ethylene/air mixtures as a function of the equivalence ratio and initial pressure.

The aviation gasoline/air mixture showed an increase in C-J speed as equivalence ratio increases from 1.0 to 1.3. No consistent trend was found for the variation with initial pressure. This could be caused by fuel composition variation, which is a property of liquid fuels like aviation gasoline. Another possibility to cause this variation is incomplete or inconsistent vaporization of the liquid fuel. The large error bars, indicating large variation in data points, supports these arguments.

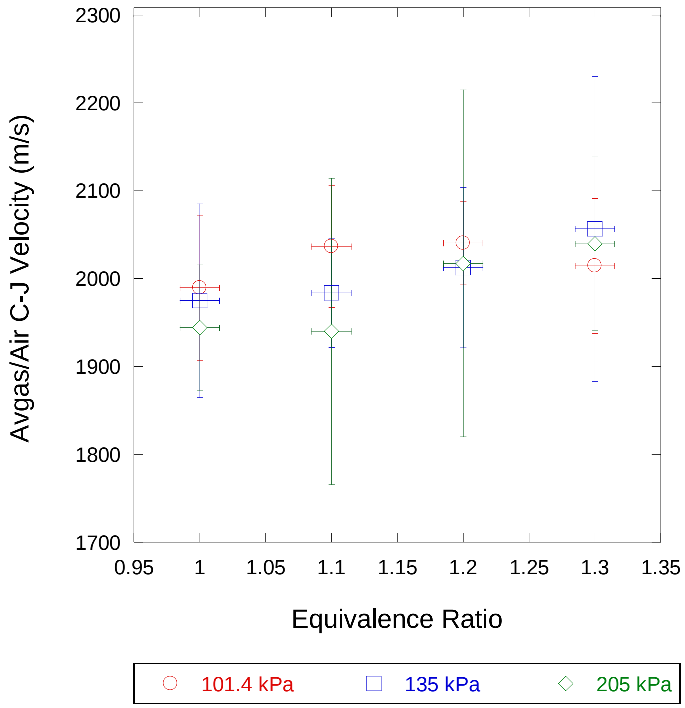

Figure 9: The C-J speeds of the aviation gasoline/air mixtures as a function of the equivalence ratio and initial pressure.

DDT Time & General Overview Plots

Shown in these plots are DDT time, ignition time, total detonation time (sum of DDT and ignition times), and Chemkin ignition time results. Each plot shows similar trends for each data set, with the exception of the DDT time for the aviation gasoline/air mixture. This trend differs from what would be expected, as the DDT distances show a decrease with higher pressures, and DDT times show minimial change and even a slight increase for the aviation gasoline/air mixture. Laminar flame speed has shown to decrease with elevated pressure, due to the competition between two body and three body chemical kinetic reactions[14]. Since laminar flame speeds are lower at higher pressure, the deflagration flame that is established at the beginning of the DDT will be slower than it is at lower initial pressures. Thus, while the DDT distance shows a decrease as pressure increases, the DDT time can increase, or show no change at all. Ethylene/air and hydrogen/air mixtures still show a slight decrease in DDT time. This is because flame speed accelerates quickly in these mixtures and a deflagration flame is only present for a fraction of the time, as compared to the aviation gasoline/air mixture.

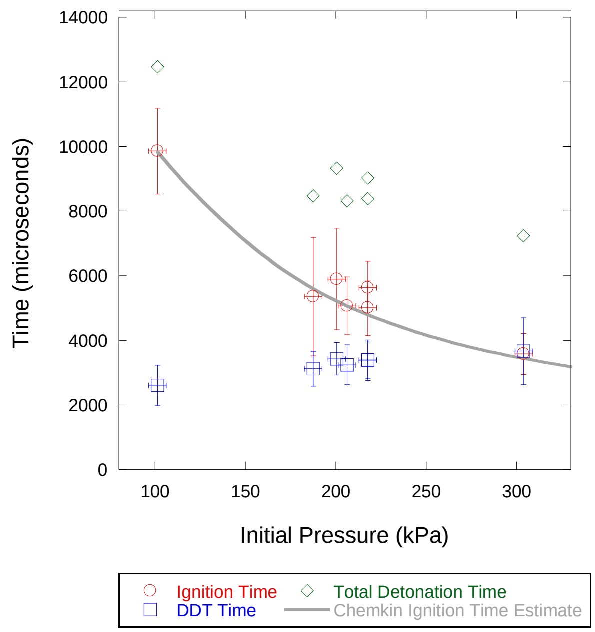

Figure 10: The ignition time, DDT time, and total detonation time of the stoichiometric aviation gasoline/air mixture as a function of initial pressure. Results are from the MSD ignition system.

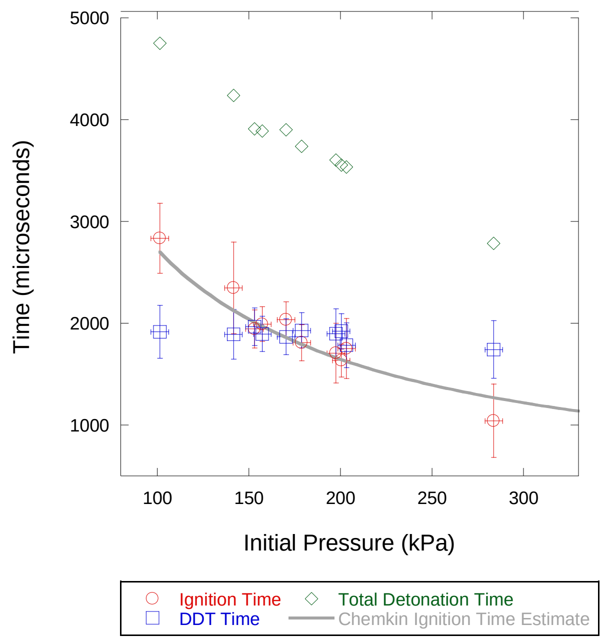

Figure 11: The ignition time, DDT time, and total detonation time of the stoichiometric ethylene/air mixture as a function of initial pressure. Results are from the MSD ignition system.

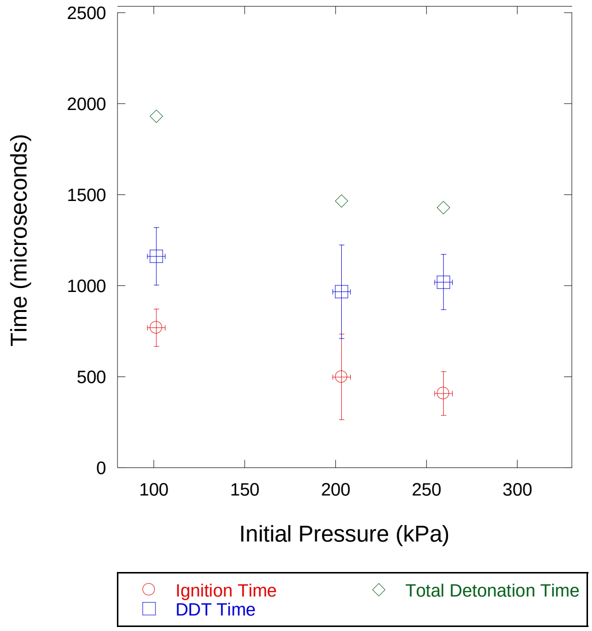

Figure 12: The ignition time, DDT time, and total detonation time of the stoichiometric hydrogen/air mixture as a function of initial pressure. Results are from the MSD ignition system.

VIII. Conclusions

Pressure scaling effects on ignition and detonation initiation have been investigated, in the pulse detonation engine, for three fuels, i.e., aviation gasoline, ethylene, hydrogen. Ignition times, DDT times, DDT distance, and C-J velocities were determined for a variety of run conditions. Measured results show a reduction in the ignition time of roughly 50% and in the DDT distance of roughly 30%, for all three fuels at an initial tube pressure of 3 atmospheres. With atmospheric initial tube pressure, the transient plasma ignition system yielded the shortest ignition times, followed by the thermal plasma ignition system, and lastly the MSD automotive ignition system. At roughly 2 atmospheres of initial pressure the thermal plasma ignition system showed no benefit over the aftermarket automotive ignition system. C-J wave speeds have shown to increase with elevated initial pressure, and agree with trends of numerical results. Pressure scaling has proven to reduce total detonation time for all mixtures tested. Increased initial tube pressures can be used to aid in detonation initiation in the PDE if a practical method of application is employed.

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