DETONATION INITIATION IN A PULSE DETONATION ENGINE WITH ELEVATED INITIAL PRESSURES

Master’s Thesis

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By
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ABSTRACT

An experimental study was done to examine the effects of elevated initial tube pressure in the PDE. Measured parameters were the ignition time, DDT run-up distance, DDT times, and C-J velocity. Mixed with air, three fuels, i.e., aviation gasoline, ethylene, and hydrogen, were tested at various initial pressures and equivalence ratios. A stock automotive ignition system was employed, along with a transient and thermal plasma ignition system, 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. At roughly 2 atmospheres of initial pressure the thermal plasma ignition system showed no benefit over the stock automotive ignition system. In addition to the experimental results, a brief Chemkin analysis was done to model the stock automotive ignition system.
To my family who have given me continuous support throughout my life.
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CHAPTER 1
INTRODUCTION

1.1: PDE History

The Pulsed Detonation Engine (PDE) is a novel propulsion concept that shows promise of many improvements over current aircraft propulsion systems. Simplicity, scalability, high specific thrust, and low emissions are among the benefits that the PDE promises (Schauer, et al. 2001). However, this wonderful propulsion concept is not yet utilized because of the challenges faced today with this still young technology.

The PDE is an improvement to the pulsejet, which was a low-cost means of propulsion used by the Germans in WWII (Bussing and Pappas 1994). The V-1 buzz bomb was the first generation cruise missile and was driven by a pulsejet. The pulse jet is an intermittent combustion propulsive device that consists of a tube with a valve on one end that only lets air into the combustion chamber, while the other end remains open to the atmosphere. To first ignite a pulsejet, air is forced into the tube through the valve, while fuel is added at a constant rate, establishing a combustible mixture. The mixture is then ignited and a deflagration flame propagates down the tube and out of the open end. The expansion of the hot combustion gases forces mass out of the open end of the pulsejet, providing thrust and creating a pressure drop in the combustion
chamber. The lower pressure opens the one-way valve, drawing in fresh air to be mixed with more fuel. The hot exhaust gases that are leaving the combustion chamber ignite the fresh mixture, causing another deflagration wave, and the process becomes self sustained as long as fuel is added (Litke, et al. 2005).

The PDE runs on a similar premise to the pulsejet. With one end closed, a detonation is sent propagating down a tube. The resulting pressure rise causes a net thrust by pushing against the closed end of the tube and the induced mass motion of the exhausting gases further propels the PDE. The biggest difference between a pulsejet and a PDE is the combustion wave structure, as the PDE involves detonation instead of deflagration. Further explanation of detonation, how it differs from deflagration, and the PDE cycle are provided in subsequent chapters.

1.2: Research Motivation

The pulsed detonation technology is still in developmental stages and one of the areas in need of improvement is in cycle frequency. Thrust produced by the PDE comes in intermittent pulses that represent each firing cycle. As the detonation wave exits the thrust tube, the increased pressure from the combustion event, and the mass motion induced by the detonation produce a thrust as the exhaust gases exit. The purge and fill phases of the PDE cycle follow the firing phase, but produce minimal thrust as they are used to setup the subsequent firing cycle. For this reason, time averaged thrust becomes important, and is calculated by integrating the thrust over the total time of one cycle (Mitrofanov and Zhdan 2004). If cycle time is reduced, while still achieving
detonation, the time averaged thrust will increase, thus increasing the thrust and the crucial value of thrust to weight ratio.

Decreasing cycle time involves faster filling operations, mixing operations, and detonation initiation. This research focuses on an attempt to reduce the detonation initiation processes by elevating initial pressures in the detonation tube. Literature has shown that increased pressures shorten the ignition delay for a wide range of mixtures. This research involves measurement of critical detonation initiation processes at multiple pressures. The measured ignition delays will be verified and supported by results found with Chemkin chemical kinetics code (Kee, et al. 2006).

Another motivation for this research is examining other effects elevated pressures may have on the detonation initiation process. Deflagration to detonation transition is currently the method used to initiate detonation in the PDE. The thrust tube must be sufficiently long for this transition to take place, or the PDE will behave more like a pulsejet. If elevating initial pressure changes transition distance, the thrust tube length can be to change likewise. So even if the frequency can be increased slightly by elevating pressure, increased tube length, or lack of detonation initiation could make implementation impractical. The objective of this research is to examine the effect of initial pressures on the detonation formation process. Analysis has shown promise that elevated pressures can shorten the ignition time of a fuel/air mixture. Since shorter firing cycles are needed to increase PDE frequency, elevated pressures need to be examined. This research entailed measuring detonation initiation processes at multiple pressures. Three different fuels, i.e., hydrogen, ethylene, and aviation gasoline, over a range of equivalence ratios will be considered. Ignition times will also be compared to
the Chemkin code (Kee, et al. 2006) results, which to solve the rate expressions, based on Arrhenius rate chemical kinetics. Measurements made in this research show the benefits and/or drawbacks associated with elevating initial pressure in the PDE tube. A higher energy thermal plasma ignition system was also explored at various pressures to verify the benefit a large spark discharge can provide to an initially elevated pressure system. The Chemkin results will also be used to better characterize the ignition system, and to verify trends developed by testing of the standard ignition system.

1.3: Thesis Layout

The information presented in this thesis is organized into 5 chapters. CHAPTER 2 presents all of the background knowledge of the PDE, as it pertains to the current research. Next, CHAPTER 3 presents the experimental facility, and the sensors used to collect the information presented. CHAPTER 4 explains the data reduction process, and presents the uncertainties accumulated in the results. Lastly, CHAPTER 5 has the results and conclusions drawn from the work.
CHAPTER 2
BACKGROUND INFORMATION

In this chapter, the background knowledge needed to understand the results that will be presented. This includes fundamental combustion theory as it pertains to the research at hand. Then an overview of the detonation phenomena including the Hugoniot Curve and ZND model, will lead into an explanation of PDE operation. The firing cycle of the PDE is further broken down to clearly indicate the different detonation initiation processes that were studied, namely ignition time and deflagration to detonation transition. Literature relating to mixture ignition and the detonation formation process are then discussed. Lastly, a brief overview of research that has been done that is directly related to the study of elevated initial pressures on detonation initiation processes.

2.1: Combustion Basics

Combustion is the reaction of a fuel and an oxidizing agent, and results in heat generation. The combustion of the fuel and oxidizer is many reactions happening simultaneously that have a net exothermic effect. Each of the reactions progresses at a finite rate in the forward and reverse direction. The combination of how these reactions progress as a whole determines the amount of time needed to combust a mixture. The
overall reaction rate is usually dominated by collisions between molecules of two species that can react with one another. Reactions that follow this are termed second-order reactions, and have the general form as shown in Eq. (2.1) (Glassman 1996, 37).

Where A and B are reactant species, and C and D are product species. To find the reaction rate of this form of Eq., we must first look at the law of mass action.

\[ A + B \rightarrow C + D \]  \hspace{1cm} (2.1)

The law of mass action states that the rate of disappearance of a species is proportional to the product of the reactant concentrations, each raised to its stoichiometric coefficient. This law has been confirmed experimentally and gives rise to a method of calculating reaction rate. A reaction of arbitrary complexity can be written as Eq. (2.2):

\[ \sum_{j=1}^{n} v_j' M_j = \sum_{j=1}^{n} v_j'' M_j \] \hspace{1cm} (2.2)

where \( M_j \) is the molar concentration of the chemical species \( j \), \( v_j' \) is the reactant stoichiometric coefficient, and \( v_j'' \) is the product stoichiometric coefficient. The summation is carried over all \( n \) species, and each specie has a specific subscript \( j \).

From the law of mass action, the rate of change of species \( i \) concentration is given by Eq. (2.3):

\[ \frac{d M_i}{dt} = v_i'' - v_i' \hspace{0.5cm} \text{ReactionRate} = v_i'' - v_i' \hspace{0.5cm} k \prod_{j=1}^{n} M_j^{v_j'} \] \hspace{1cm} (2.3)

where \( k \) is a proportionality constant that is termed the specific reaction rate coefficient. Further explanation of these equations is available in (Glassman 1996, 36).
The reaction rate of the general second-order reaction can be defined. Combining Eq.’s (2.3) and (2.2), the reaction rate of $A$ in an irreversible reaction is derived as Eq. (2.4).

$$- \text{ReactionRate} = \frac{d}{dt} A = -k \ A = -\frac{d}{dt} C = -\frac{d}{dt} D$$ (2.4)

Each bracketed species denotes the concentration of the species. Positive reaction rate pertains to an increase in the specie of interest. There are different theories that define $k$. For a second-order reaction, Arrhenius proposed a simple theory that makes the proportionality constant temperature dependent (Glassman 1996, 39).

The Arrhenius rate expression states that only molecules that contain energies greater than the activation energy will react. Following this logic, Arrhenius derived the Arrhenius rate expression, which has different forms, but the most general form is shown in Eq. (2.5). For greater detail of the Arrhenius rate expression, refer to (Glassman 1996, 37).

$$k = A \exp \left( -\frac{E}{RT} \right)$$

$$A = A \ T^{\frac{1}{2}}$$ (2.5)

Where $E$ is the activation energy, $R$ is the universal gas constant, $T$ is temperature, and $A$ is the “kinetic pre-exponential $A$ factor”, which is dependent on the square root of temperature. In many cases this dependence is ignored since the exponential factor is much more powerful (Glassman 1996, 39). So $A$ is a prescribed constant in this case.

Another very important variable used in combustion science is equivalence ratio. If we look at the combustion of hydrogen in oxygen, the balanced reaction will look like Eq. (2.6).
So the ideal fuel and oxygen ratio should be 2 moles of diatomic hydrogen for every mole of diatomic oxygen. This is known as the stoichiometric ratio. It can be converted to the ratio of hydrogen mass to oxygen mass by using atomic weights.

\[
\left( \frac{\text{fuel}}{\text{oxygen}} \right)_{\text{stoich}} = \frac{2 \text{ mol } H_2}{1 \text{ mol } O_2} = \frac{2 \frac{\text{g}}{\text{mol}} H_2}{1 \frac{\text{g}}{\text{mol}} O_2} = \frac{1 \text{ g } H_2}{8 \text{ g } O_2}
\]

The equivalence ratio \( \phi \) is the actual ratio of fuel to oxidizer over the stoichiometric ratio.

\[
\phi = \frac{\frac{\text{fuel}}{\text{oxidizer}}_{\text{actual}}}{\frac{\text{fuel}}{\text{oxidizer}}_{\text{stoich}}}
\]

Combustion strongly depends on this ratio. In my experiments, equivalence ratio was one of the primary factors varied in testing. Mixtures with equivalence ratios greater than one have more fuel than can be combusted by the given amount of oxidizer, and are called “fuel rich” mixtures. Mixtures with equivalence ratios lower than one have more air than needed to combust the fuel, and are called “fuel lean” mixtures.

The oxidizer used for these experiments was air, which is assumed to be a mixture of 21% diatomic oxygen and 79% diatomic nitrogen. Table 2.1 shows the stoichiometric fuel to air mixture ratio for each of the fuels studied.
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Chemical Formula</th>
<th>Fuel/Air Ratio (mass basis)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>0.0291</td>
</tr>
<tr>
<td>Ethylene</td>
<td>C₂H₄</td>
<td>0.0700</td>
</tr>
<tr>
<td>Aviation Gasoline</td>
<td>C₈.13H₁₅.₃₄</td>
<td>0.0521</td>
</tr>
</tbody>
</table>

*Air composition assumed to be 21% oxygen and 79% nitrogen

Table 2.1: Stoichiometric fuel/air ratios for fuels tested

The aviation gasoline has a chemical formula with decimal values for elements carbon and hydrogen. Aviation gasoline is a combination of many liquid hydrocarbons. Analysis of the fuel by the manufacturer shows that the fuel can be approximated as having a chemical composition of C₈.1₃H₁₅.₃₄, based on the molecular ratio between carbon and hydrogen. This composition is used for calculation, but represents no physical compound.

2.2: Detonation

As previously stated, the major difference between a pulsejet and a PDE is the combustion wave structure. A deflagration is defined as a subsonic combustion wave, while a detonation is a supersonic combustion wave (Kuo 1986, 233). The deflagration wave is an approximately constant pressure process, since the process is relatively slow allowing the gases to expand. Since a detonation wave propagates supersonically, the wave travels faster than expansion waves, providing no time for expansion of the gases ahead of the wave. This leads to a sharp pressure rise as if the combustion took place at constant volume. The differences between deflagration and detonation are very well spelled out in Table 2.2 (Glassman 1996, 223).
<table>
<thead>
<tr>
<th>Ratio</th>
<th>Usual Magnitude of Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Detonation</td>
</tr>
<tr>
<td>( \frac{u_d}{c_u} )</td>
<td>5-10</td>
</tr>
<tr>
<td>( \frac{u_b}{u_u} )</td>
<td>0.4-0.7</td>
</tr>
<tr>
<td>( \frac{P_b}{P_u} )</td>
<td>13-55</td>
</tr>
<tr>
<td>( \frac{T_b}{T_u} )</td>
<td>8-21</td>
</tr>
<tr>
<td>( \frac{\rho_b}{\rho_u} )</td>
<td>1.4-2.6</td>
</tr>
</tbody>
</table>

Table 2.2: Qualitative difference between deflagration and detonations in gases.

In Table 2.2, \( u_u \) is the velocity of the of the wave, \( c_u \) is the speed of sound in the unburned gases, \( u_b \) is the velocity of the burned gases, \( P_b \) and \( P_u \) are the pressures of the burned and unburned gases, respectively, \( T_b \) and \( T_u \) are temperature of the burned and unburned gases, respectively, and \( \rho_b \) and \( \rho_u \) are the densities of the burned and unburned gases, respectively. Note that a large pressure rise occurs in a detonation wave, as a contrast to the slight pressure drop of the deflagration wave. The density ratios have a similar trend, as a result of the pressure changes, and as stated before, the detonation travels at a supersonic speed, while the Mach number of the deflagration is subsonic.

Deflagration waves will tend towards a particular “laminar flame speed” that depends on, among other things, the rate of energy release (Glassman 1996, 119). Once detonation is initiated, the wave speed will always stay at a specific velocity that is dictated by the composition and thermal state of the unburned mixture. This velocity is the Chapman-Jouguet velocity or the C-J speed for short. This phenomenon can be
explained through the Rayleigh line and Hugoniot curve. Derivation of the equation assumes that a detonation wave is a point discontinuity. The theory would directly relate the flow information before and after the detonation wave. To derive these equations, we begin with conservation of mass, momentum, and energy.

Mass: $$\rho_1 u_1 = \rho_2 u_2$$ (2.8)

Momentum: $$P_1 + \rho_1 u_1^2 = P_2 + \rho_2 u_2^2$$ (2.9)

Energy: $$C_p T_1 + \frac{1}{2} u_1^2 + q = C_p T_2 + \frac{1}{2} u_2^2$$ (2.10)

Where the densities ($\rho_i$), temperatures ($T_i$), pressures ($P_i$), and velocities ($u_i$) are all defined as the values before or after the shockwave with subscripts one (1) and two (2) respectively, as shown in Figure 2.1. The top graphic is the definition of the velocities used to derive the Hugoniot and Rayleigh equations. The detonation wave is assumed to be moving at a constant speed, and the coordinate is fixed to the detonation wave. The bottom graphic shows how the defined velocities relate to a stationary frame of reference with the detonation wave propagating by. The detonation in this case is propagating into a quiescent combustible mixture, as there is minimal motion in the tube before the detonation wave. The other variables in the conservation equations are the specific heat of the mixtures, $C_p$, and the heat released during combustion, $q$. 
Substituting Eq. (2.8) into Eq. (2.9), we get the equation for the Rayleigh line (2.11).

Eq. (2.8) can also be used to substitute $u_2$ in place of $u_1$ in the Rayleigh line Eq. (2.12) (Glassman 1996, 227).

$$u_1^2 = \frac{1}{\rho_1^2} \left[ \frac{P_2 - P_1}{\frac{1}{\rho_1} - \frac{1}{\rho_2}} \right]$$  \hspace{1cm} (2.11)
\[ u_2^2 = \frac{1}{\rho_2^2} \left( \frac{P_2 - P_1}{\left( \frac{1}{\rho_1} - \frac{1}{\rho_2} \right)} \right) \] (2.12)

The speed of sound can be calculated by Eq. (2.13) and when combined with the ideal gas law (2.14), we can rearrange the Rayleigh line equation to calculate wave Mach number instead of wave velocity (2.15).

\[ c_1^2 = \gamma RT_1 = \frac{\gamma P_1}{\rho} \] (2.13)

\[ P_1 = \rho_1 RT_1 \] (2.14)

\[ \gamma M_1^2 = \left( \frac{P_2}{P_1} - 1 \right) \left[ 1 - \frac{1}{\rho_2} \right] \] (2.15)

To proceed, the Hugoniot curve is then derived. Starting with Eq. (2.10), we assume specific heats are constant and substitute (2.16) and (2.14) to get Eq. (2.17).

\[ C_p = R \left[ \frac{\gamma}{\gamma - 1} \right] \] (2.16)

\[ \frac{\gamma}{\gamma - 1} \left( \frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right) - \frac{1}{2} u_1^2 - u_2^2 = q \] (2.17)

Then substituting the Rayleigh line Eq.’s (2.11) and (2.12) into Eq. (2.17), the Hugoniot equation will result (2.18) (Glassman 1996, 228).

\[ \frac{\gamma}{\gamma - 1} \left( \frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right) - \frac{1}{2} P_2 - P_1 \left( \frac{1}{\rho_2} + \frac{1}{\rho_1} \right) = q \] (2.18)
The Rayleigh and Hugoniot equations can now be used to show five regions with valid detonation solutions. The Rayleigh line equation can be rearranged into a slope intercept format as shown in Eq. (2.19).

\[ P_2 = -u_1^2 \rho_1^2 \left( \frac{1}{\rho_2} \right) + P_1 + u_1^2 \rho_1 \]  

(2.19)

Where \( \rho_1 \) and \( P_1 \) are conditions of the unburned mixture and are known. Thus, pressure \( P_2 \) and specific volume \( 1/\rho_2 \) behind the detonation wave are the only unknowns, and are linearly related with a slope given by \( -u_1^2 \rho_1^2 \).

The Hugoniot curve can also be graphed on a P-v diagram with a given value for \( q \). If \( q \) is set to zero, the Hugoniot equation is valid for property changes across a shock wave. So with an arbitrary, positive, nonzero value for heat release, the Hugoniot curve and the Rayleigh line are plotted in Figure 2.2. The Hugoniot curve yields all possible values of \( P_2 \) and \( 1/\rho_2 \) for a given \( P_1 \), \( 1/\rho_1 \), and heat release \( q \) (Glassman 1996, 229).
The Hugoniot curve has five sections, labeled with roman numerals, representing five solution regions. Also, five points are labeled with letters “A” through “E”, and represent the break points between the regions. Point “A” is the starting point, or mixture conditions ahead of the wave. The Rayleigh lines are intentionally drawn tangent to the Hugoniot curve, as Points “B” and “E” are known as the Chapman-Jouguet points, often referred to as C-J points. Point “C” is where the post wave density is the same as the initial density, and “D” is where the post wave pressure is identical to the initial pressure. Region III is the portion of the Hugoniot curve between Points “C” and ”D”, and for the Rayleigh line to hit the curve in this section, the slope must be
positive. Since the slope of the Rayleigh line is \(-u_1^2 \rho_1^2\), a positive slope would not yield a real wave velocity, and thus region III can be excluded from the possible solutions. Regions I and II are detonation solutions, and yield high velocity, as can be seen by the steep negative slope, and compression as indicated by the density increase. Regions IV and V represent the solutions for a deflagration flame, as can be understood from a much lower velocity, and an expansion wave instead of a compression wave.

Chapman was the first to recognize the C-J point as a special point on the Hugoniot curve. Chapman showed through derivation that the line from Point “A” to Point “B” is the adiabatic process (Glassman 1996, 231). Moreover, Chapman showed that the wave speed at the C-J point is sonic with respect to the burned gases. Using this information, the remaining regions from Figure 2.2 can be further classified.

<table>
<thead>
<tr>
<th>Region</th>
<th>Classification</th>
<th>Gas Velocity</th>
<th>Unburned</th>
<th>Burned</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Strong Detonation,</td>
<td>P_2 &gt; P_B</td>
<td>Supersonic</td>
<td>Subsonic</td>
</tr>
<tr>
<td>II</td>
<td>Weak Detonation,</td>
<td>P_2 &lt; P_B</td>
<td>Supersonic</td>
<td>Supersonic</td>
</tr>
<tr>
<td>IV</td>
<td>Weak Deflagration,</td>
<td>P_2 &gt; P_E</td>
<td>Subsonic</td>
<td>Subsonic</td>
</tr>
<tr>
<td>V</td>
<td>Strong Deflagration,</td>
<td>P_2 &lt; P_E</td>
<td>Subsonic</td>
<td>Supersonic</td>
</tr>
</tbody>
</table>

Table 2.3: Classification of Hugoniot curve regions.

In Table 2.3, P_B and P_E are the detonation and deflagration pressures at the two C-J points, respectively. The gas velocity is relative to the detonation wave. Since the
increased pressure causes an increase in temperature, the speed of sound in the burned gases increases for stronger detonation. It can be shown (Glassman 1996, 240) that the increase in speed of sound is greater than the increase of the burned gas velocity for the strong detonation region. Since the Mach number at the C-J point is sonic, this results in a subsonic burned gas Mach number. So when a gas mixture goes through a strong shock, the velocities relative to the wave are supersonic in the unburned gases and subsonic in the burned gases. Similarly, a pressure drop results in a slight temperature decrease, resulting in supersonic to supersonic flow for the weak detonation region. This logic is also extended to the deflagration regions. Table 2.3 summarizes these findings.

With this information, a final solution set can be determined for the Hugoniot Curve. For a strong deflagration, the burned gases could have supersonic speeds. In a constant area duct, there cannot be effective heat addition with supersonic propagation. Thus, strong deflagrations are not physically possible and can be eliminated from consideration. The strong detonation cannot be eliminated from consideration, but strong detonations are not stable. Unless the strong detonation is supported, the wave will move toward the C-J condition. Jouguet showed that the speed of sound in the burned gases is greater than the mass motion velocity \( u_s \) (Glassman 1996, 234). Thus, rarefaction waves are capable of catching the detonation wave and reducing the pressure behind the wave. These rarefaction waves can be created by a number of sources including heat loss or friction. As the pressure reduces, the wave shifts down the Hugoniot curve towards the C-J point. Once the wave reaches C-J velocity, the speed of sound plus the mass motion velocity is equal to the speed of the wave, thus a
rarefaction wave no longer can catch up to the detonation wave. So if a strong
detonation is initiated, it shifts down the Hugoniot curve to the C-J condition and then
becomes a stable, self supporting, constant velocity wave.

Figure 2.3: Hugoniot and Rayleigh lines modeling strong detonation event.

Figure 2.3 shows a strong detonation event, and provides reasoning as to why
the weak detonation solution can also be ignored. Shown in Figure 2.3 are two
Hugoniot curves, the solid curve is with an arbitrary, positive heat release, and the
dashed curve is for no heat release or a shock wave. Also shown in Figure 2.3 are two
Rayleigh lines, the dashed line is for solutions of either strong or weak detonations, and the solid line from Point “A” to Point “B” is the Rayleigh line for the C-J condition.

The structure of a detonation wave has been determined to be a shock wave followed by a combustion zone, as will be described in Section 2.3. Starting at the unburned gas state, Point, “A”, the gases pass through the shock, following the zero heat release Hugoniot curve to Point “F”. Then from “F”, combustion takes place, and the state follows the Rayleigh line to “G”, where the combustion reaches completion. Then, as previously described, the strong detonation (“G”) will shift down to the C-J point, “B”, where it will stabilize and propagate at the C-J velocity.

From this very process, the weak detonation region can be disregarded. Jouguet stated that a weak detonation is a supersonic to a supersonic air motion condition. Once the sonic condition is achieved (C-J), extra energy would need to be expended to further accelerate the flow to supersonic motion. Since all combustion energy is expended during the burning process (“F” to “G”), no more energy is available to further accelerate the flow. Thus, weak detonation can be disregarded from the solution set, and the valid solution set can be compiled, where strong detonation is a dashed line since it is not a stable condition (Figure 2.4).
2.3: ZND Detonation Wave Structure

Independently, Zeldovich, Von Neumann, and Doring all came up with further analysis of the structure of a detonation wave. This structure is known as the ZND model, which entails a shock wave followed by an attached combustion zone. The theory is that a shock wave, traveling at the C-J speed, passes through the unburned gases resulting in rapid heating and compression. No chemical reaction is assumed to happen in the shock wave portion of the detonation, since the shock wave zone is very narrow. The gases following the shock wave are assumed to be heated and compressed...
enough to lead to a deflagration, which has high enough reaction rates that the flame can keep up with the shock wave. The combustion, therefore, supports the shock wave and takes place in the wake of the shock wave.

Figure 2.5: Property variation through a ZND detonation wave (Kuo 1986, 261).

Figure 2.5 shows the variation of some properties through the ZND detonation wave structure (Kuo 1986, 261). The shock wave is a very slim section of the total length of the combustion wave. The temperature (T) spikes across the shock wave, then raises again from the actual combustion event, following the “induction period”. The induction period is the time needed for the chemical kinetics to reach a high enough
temperature to combust. Pressure (P) and density (ρ) both spike through the shock wave and hold relatively constant until they relax through the deflagration event.

The ideal ZND model is shown in Figure 2.6, and the actual ZND model is drawn in close parallel in Figure 2.7.

Figure 2.6: Ideal ZND P-v diagram.
The major difference between the ideal curve and ZND curve is that the ZND model doesn’t quite reach Point “F” of Figure 2.6. Instead, the ZND model reaches the “von Neumann spike”, which is the peak pressure behind the shock wave, before the chemical reactions reduce the pressure. Multiple paths exist to the C-J point in Figure 2.7, the first of which, “a”, is the limit of chemical kinetics happening at the leading edge of the shock wave. Since there is no compression at the leading edge of the wave, the temperature would not be great enough to initiate reaction, so this path would not be sustainable (Kuo 1986, 262). Paths “b”, “c”, and “d”, represent different chemical kinetic rates. Path “b” would have the fastest kinetics of these three, since the von Neumann spike happens at a lower pressure than the other two. The lower pressure for the von Neumann spike is a product of fast reaction kinetics, where the deflagration wave begins to relax the pressure before the complete pressure rise from the shock wave

Figure 2.7: P-v diagram of actual ZND detonation wave (Kuo 1986, 262).
can be achieved. So the lower pressure is a product of faster chemical kinetics. Thus, route “b” has faster kinetics than either routes “c” or “d”. By similar theory, route “d” represents the slowest chemical kinetics of the three paths presented.

2.4: Multidimensional Detonation Wave Structure

Though the basic structure of a detonation can be well characterized with a one-dimensional analysis such as the ZND model, it is in general a three-dimensional phenomenon. (Campbell and Woodhead 1927) first realized that a detonation is a locally multidimensional, unsteady wave. They noticed spinning in circular tubes filled with mixtures near combustibility limits. This was assumed to be a special property of only combustibility limit mixtures. Later, (Denisov and Troshin 1960) used soot-covered plates to record thin lines left by a passing detonation. Figure 2.8 shows a typical diamond pattern that is left in the soot trace by the detonation wave.
The trace is created by what is known as the “triple point”. This is the intersection of the incident shock wave, reflected shock wave, and the Mach stem as shown in Figure 2.9.
The triple points are the intersection of the incident shock, reflected shock, and Mach stem. The shock structure is created due to shock reflection with respect to a symmetric plane. There are multiple triple points traversing up and down across the detonation front, while the wave propagates down the tube. Each triple point would trace out a line, in the space-time domain, which can be visualized in the soot trace on the pipe wall. Once the detonation wave passes a soot-covered location, the diamond-like detonation cell is drawn into the soot by the moving triple points (Fickett and Davis).
Further explanation of detonation cell formation is found in (Fickett and Davis 1979, Kuo 1986).

The detonation cell size has shown to be related to the combustion characteristics of combustible mixtures.

\[ T_{\text{Induction}} \propto \lambda \]
\[ E_{\text{Activation}} \propto \lambda^3 \]

First, the cell size is proportional to the induction time \( T_{\text{Induction}} \), which in turn is an indicator of the rate of chemical kinetics (Glassman 1996, 256). Another observation is that the activation energy, \( E_{\text{Activation}} \), is proportional to the cube of the cell size (Schauer, et al. 2005). This means that if one mixture has half the cell size of another mixture, the mixture with the smaller cell size will require one-eighth of the activation energy required for the mixture with the larger cell size.

2.5: The Pulsed Detonation Engine

The Pulsed Detonation Engine (PDE) runs on a three-phase cycle: fill, fire and purge. The fill phase is when a fresh mixture of fuel and air is introduced to the detonation tube. The fire phase starts following the closing of the fill valves and includes spark discharge, ignition, the DDT process, and time for the combustion wave to propagate down the tube and exhaust. The purge phase then introduces fresh air into the tube to cool the tube walls and internal components, and to separate the fire phase from the incoming fuel and air mixture. A schematic of the overall process is shown in Figure 2.10, where one revolution is equivalent to one cycle. Each phase is one third of the circle, as each phase gets one third of the time allotted per cycle.
Thrust is produced by the PDE from the pulsating pressure rises caused by detonations, and is a part of the fire phase of the cycle. The higher the frequency of detonations, the more thrust that will result. To increase frequency of the PDE cycle, each phase of the cycle must happen faster. Thus, among other improvements, the fire cycle must happen in a shorter time span.
2.6: Mixture Ignition

The PDE fire phase has multiple time scales that need to be considered in order to shorten the entire process. Figure 2.11 shows a timeline of the processes needed to complete the fire phase.

![Figure 2.11: PDE firing phase timeline.](image)

The ignition delay is defined in this timeline as the time from valve closing to when the spark is discharged. This time can be varied and optimized for different run conditions. Ignition time is the time from the spark to when a deflagration flame is first established. This will be the topic of this section, while deflagration to detonation transition and detonation propagation will be covered in Section 2.7.

Ignition of a mixture can be achieved in multiple ways, of which external ignition processes can be classified into three different categories. The first is ignition by thermal energy, where heat is introduced to the mixture through any means of heat transfer. The temperature, once high enough, will set off the chemical reactions and
combustion will ensue. The next of the three is ignition through chemical stimuli. This is the introduction of hypergolic materials that will immediately ignite once in contact. This is a reliable and easy method for ignition used in rockets, but requires extra chemicals that would have to be carried by the airframe. The final method is through mechanical stimulation such as a shock wave (Kuo 1986, 735). For the PDE, ignition from a sparkplug produces a thermal means of ignition. This method initiates the deflagration flame that starts the fire phase. However, once the deflagration transitions to a detonation, the shock wave associated with the detonation acts more like mechanical stimulation to ignite the unburned mixture. This concept is explained thoroughly in Section 2.3.

An explanation of the effect of initial pressure on ignition time is presented by (Lefebvre 1986, 6). Chemical kinetics is governed by many interwoven reactions that occur simultaneously. These reactions and their rates control the ignition times and other burning properties of combustion. A common simplification made for combustion is the use of global reaction theory, which describes the entire reaction in one step, and yields a practical solution for a complex system (Lefebvre, et al. 1986). When using global reaction theory, the reaction rate is described by Eq. (2.20).

\[
Reaction \ Rate = RR = K \ oxygen \ j \ fuel \ m \ P^n
\]  

(2.20)

Where \( j \) and \( m \) are stoichiometric coefficients, \( P \) is the pressure, \( n \) is an experimentally determined constant, \( oxygen \) and \( fuel \) are the molar concentrations of the oxygen and fuel, respectively. \( K \) is the reaction rate constant and is defined by Eq. (2.21).
Where $A$ is the Arrhenius constant, $T$ is the temperature, $E$ is the global activation energy, and $R_u$ is the universal gas constant. The ignition time is proportional to the inverse of the reaction rate, thus giving Eq. (2.22) that correlates ignition time and pressure.

$$IT \propto \frac{1}{RR} = \frac{1}{A} \text{oxygen}^{-j} \text{fuel}^{-m} P^{-n} T^{-0.5} \exp \left( \frac{E}{R_u T} \right)$$

(2.22)

Since pressure has a negative exponent, higher pressures will lead to lower ignition times of the mixture, based on global reaction theory. Also, increasing initial temperature will decrease ignition time. This theory is an empirical extension of finite rate kinetics, which was illustrated in Section 2.1.

### 2.7: Detonation Initiation

Detonation waves provide very large pressure rises, and are the key to the PDE thrust. Establishing a detonation in a shorter amount of time will also help to increase engine frequency, which will increase thrust. The detonation wave can be established by way of direct ignition or by DDT. These two ways to initiate a detonation in the PDE will be discussed in this section.

Direct initiation of a detonation would be a great way to minimize the firing cycle time of the PDE. With only the duration of a spark to establish the supersonic combustion wave, the DDT time will no longer be an issue in the fire phase. Moreover, the tube length can be shortened since the run-up distance for DDT is not needed. The wave propagation time can be minimized by shortening the detonation tube to a
minimal length, which will in turn decrease the time period needed for each PDE cycle and reduce the weight of the structure.

The problem with direct detonation initiation is that a large amount of energy is required. Figure 2.12 shows the direct initiation energies for hydrogen/air and ethylene/air mixtures as compared to equivalence ratio (Kaneshige and Shepherd 1997).

Figure 2.12: Direct detonation initiation energies for hydrogen and ethylene mixtures.

The minimum energy value for a hydrogen and air mixture is at an equivalence ratio of about 1.05, which has a required energy of slightly over 4200 joules. This is an
enormous amount of energy to discharge in a single spark. For ethylene the minimal energy is at an equivalence ratio of around 1.5 and a minimal energy of just over 27 kilojoules.

Figure 2.13: Direct detonation initiation energy compared to initial pressure.

Figure 2.13 shows how direct initiation energies vary with initial pressure for a hydrogen and oxygen mixture (Kaneshige and Shepherd 1997). Even with this easily detonable mixture, the initiation energy at atmospheric conditions is above 12 joules. A positive trend is that with increasing pressure, initiation energy is decreasing. However,
when a hydrogen/air mixture is employed, a much larger decrease in initiation energy will be needed. The very large direct initiation energies would require extremely powerful electrical equipment that would consume a lot of energy, add substantial weight to the engine, and cause possible electromagnetic interference with aircraft controls. Therefore, direct initiation, while an attractive option, is rather impractical for application in the PDE.

Another way, and the current method being studied, is to use DDT to create a detonation. After the initial deflagration flame is ignited, the products behind the flame expand as a result of their increased specific volume. This expansion sends compression waves forward from the combustion front, heating the unburned gases ahead and increasing the speed of sound. The increased speed of sound allows subsequent compression waves to catch up and coalesce with the initial compression waves. The preheating also increases the flame speed, which further disturbs the unburned gases to the point where turbulence begins to appear ahead of the combustion. This turbulence would further accelerate the combustion wave to the point that a shock wave would form. Once the shock wave is established, the high increase of temperature created by the shock wave would initiate the combustion, and the compression waves sent forth from the combustion sustain the shock front (Glassman 1996, 223). These steps compose the DDT process, and once complete create a self sustaining detonation wave.

It is important to note that DDT will only take place when the combustion wave is confined. A nice way to visualize the DDT process is the hot combustion gases expanding and pushing the wave forward like a piston, until the wave achieves
detonation velocities. If the tube is enclosed on one end and lit at the open end, the exhaust gases will expand out of the tube, and the flame will remain a deflagration traveling at the laminar wave speed (Kuo 1986, 265). Similar results will ensue if both ends of the tube are open, the tube is full of a detonable mixture, and ignited at one end. With no barrier for the expansion to push off, the combustion wave will never exceed laminar flame speed.

To accelerate the DDT process, a Shchelkin spiral is used to induce turbulence and create hot spots. Highly detonable fuels such as hydrogen or acetylene mixed with air have a transition distance on the order of a meter (Glassman 1996, 224), but practical PDE fuels, such as aviation gasoline and JP-8, require much greater run-up distances for DDT. Increased DDT distance requires more mixture/fuel and causes the PDE to weigh more due to increased tube length. Also, the longer DDT takes the more time it adds to the fire phase of the PDE, which reduces the operating frequency of the engine.

The Shchelkin spiral is a coil that is placed against the interior wall of the detonation tube, creating turbulence and increased mixing. The increased turbulence and flame mixing accelerates the flame front, allowing faster DDT (Figure 2.14). It is accepted in the research community that other obstacles that increase turbulence and mixing would decrease transition time as well (Litchford 2001). For the present research, a Shchelkin spiral was used as it is widely known and accepted as a means of accelerating the DDT process.
Figure 2.14: Effect of Shchelkin spiral in detonation tube (Litchford 2001).

Figure 2.15 shows the DDT, direct ignition, and deflagration combustion wave trajectories. “X” represents the distance down the combustion tube, and “t” represents the time passed. The slope of the line is the reciprocal of the wave velocity, which is why both the direct ignition detonation and deflagration flame have a similar and constant slope after initiation. The direct ignition slope is the reciprocal of the C-J speed, and the deflagration slope is the reciprocal of the flame speed. The DDT wave starts at the same slope as the deflagration wave, and then gradually accelerates or transitions to the slope of the detonation wave. This graphic displays the time and tube distance savings that would result from the direct initiation technique, if a viable direct initiation method was employed.
Figure 2.15: Trajectory of flame for a deflagration, DDT, and direct ignition detonation wave (Litchford 2001).

2.8: Recent Related Research

Many research efforts have been focused on the effect of nozzles on PDE detonation tubes (Kailasanath 2001, Knick 2006, Yungster 2003). Many numerical simulations have yielded results for the effect of both converging and diverging nozzles on PDE performance. Yungster has shown numerically that a diverging bell nozzle increases specific impulse of the PDE. Others have come to the same conclusion as stated by (Kailasanath 2001). The nozzle configuration that pertains to the current research is that of a converging nozzle. The converging nozzle will restrict flow out of the tube when fill and purge gases flow into the tube, evacuating either exhaust or purge
gases. This leads to an increase in detonation tube pressure, until enough mass flows out for the tube to return to atmospheric conditions. (Knick 2006) was able to compare the initiation processes to the initial pressure in the detonation tube for a hydrogen/air mixture at an equivalence ratio of one.

![Figure 2.16: Ignition time, detonation time and DDT time as compared to initial pressure (Knick 2006).](image)

The data in Figure 2.16 shows a reduction of ignition time from initial pressure up to a pressure of roughly 160 kPa, but then a slight increase in ignition time as
pressure continues to increase. The increase at higher pressures contradicts what other research has shown (Lefebvre, et al. 1986). One possible source for this trend is a nozzle flow fluctuation reported by Knick.

The major limitation of Knick’s setup is explained with the comparison of ignition time to ignition delay. He showed that there were benefits from the nozzles when the ignition delay was set to zero, but when the ignition delay increased, the results quickly showed no benefit over the standard running conditions. This can be attributed to the fast blow down time of his setup. The nozzle restricts the flow through the tube, increasing the pressure. With more flow, higher pressures can be achieved, and more mass flow is forced through the restricting orifice. As pressures increase, the pressures will remain elevated for shorter periods of time, and could cause a transient pressure condition when ignition is attempted. The setup used in this research uses a tank on the end of the detonation tube. The tank increases the volume that is pressurized, causing the setup to remain at higher pressure for a longer period of time. Knick’s testing was also only done for hydrogen/air mixtures, which is not practical for aviation purposes, due to the low energy density. The testing for this research will be carried out with hydrogen/air, but also ethylene/air and aviation gasoline air.

Other research related to initial pressure was conducted by (Chapin, et al. 2007). This research group varied mixture velocity, initial pressure, and temperature to examine how these parameters affect the DDT processes. A very similar setup to the one used in this research was employed. Not many numerical results were presented by Chapin et al. Instead of tabulated numerical values over a range of operating conditions, Chapin et al. used their results to determine a curve fit equation to predict
DDT measurements. As was done by Knick, only hydrogen/air mixtures were tested.

So while previous research done by Chapin et al. is similar to this thesis, very little was published, and the fuel tested is not practical for aviation.
CHAPTER 3
SETUP AND PROCEDURES

This chapter illustrates the experimental setup. Emphasis is placed on methods and procedures used in the present research to arrive at the major conclusions of the work. General information about the facilities are presented, followed by an in depth description of the research PDE at AFRL. The support systems such as the air and fuel delivery and measurement will also be described to give a complete picture of how each parameter is controlled. Next, a thorough explanation of the ignition systems employed will be provided. Then, the method of data collections is described, along with the procedure used to change the parameters. Lastly, an explanation of the Chemkin analysis methods will be presented.

3.1: General Facility

The Pulse Detonation Research Facility (PDRF), located at Wright Patterson Air Force Base (WPAFB) was built in 1997, with the main goal of creating an air breathing, practically fueled pulse detonation engine (PDE). To date, flash vaporization, plasma ignition systems, branched detonation, pre-detonators, and many other technologies have been developed and tested in this facility. Scientists at PDRF also built and flew
the first ever PDE propelled aircraft in 2008 (Warwick 2008). This established PDE lab is where the experimental testing for this study was done.

The facility is a 750,000 $ft^3$ explosion proof test cell, containing a PDE prototype mounted on a damped thrust stand capable of measuring up to 1,000 $lb$ of thrust. This thrust stand allows for accuracy at lower thrust levels. The 1,000 $lb$ thrust stand is mounted to a larger 60,000$lbf$ thrust stand in case the need for larger measurement arises. The rig is remotely controlled from a control room that is protected from the test cell by a wall that is minimum 2 feet thick, comprised of reinforced concrete. This wall ensures the safety of researchers in case of a catastrophic event, and shields personnel from the high decibel level noises produced by the PDE.

3.2: The Pulse Detonation Research Engine

The first PDE at PDRF was built using a GM Quad-4 Dual Overhead Cam (DOHC) cylinder head, with tubes in place of the four cylinders. The cylinder head’s valves are controlled flow orifices for fill and purge gases and the DOHC provides balanced timing. There are 4 valves for each tube; the two valves that were the cylinder intake are used to fill the tube with the fuel and air mixture, while the two exhaust valves are used to flow purge gases. Figure 3.1 shows the mounting block without the PDE thrust tubes attached. There are locations for four thrust tubes, and inside each bay, the valves can be seen. The top two valves are the fill valves, and the bottom two valves are the purge valves. Also visible in this graphic, are the holes below the valves where the PCB pressure transducers measure head pressure.
Purge gases cool the inside of the tube and prevent backfire by shielding the incoming fuel and air mixture from the previous combustion products. Cooling oil flows through the cylinder head to prevent overheating. An electric motor is used to turn the cam shafts and control the frequency of the machine. The cam shafts and gearing set the valve sequence and timing. The head is designed to deal with combustion events and has proven to be very durable and dependable.

The PDE is mounted to the thrust stand, with tubes firing horizontally into an exhausting tunnel as shown in Figure 3.2.
The detonation tubes on the PDE are interchangeable with 1”, 2”, and 3.5” schedule 40 pipes readily available at PDRF. For the experiment discussed here, 2” schedule 40 pipe was used. Two detonation tubes were setup, each tube having a length of 82” from the cylinder head to the end of the tube. Shown in Figure 3.2 is a typical PDE setup, where the tubes are open to the atmosphere. With the engine running like this, the initial pressure, at the closed end, fluctuates about 1atm (Helfrich 2006). This is the baseline test configuration that is compared to elevated pressure results.

For this experiment, the setup needed to have the capability to elevate the initial tube pressure. To elevate the initial pressure, large tanks were added to the end of the tubes with an exhausting orifice diameter of 0.80in(0.020m), which is much smaller than the tube diameter (Figure 3.1). The restricting effect of this smaller orifice increased the pressure inside of the tank and tube.
With this setup, there are two basic ways to increase the pressure in the tubes. They both come back to the concept of a choked orifice, whose mass flow is governed by Eq. (3.1) (Anderson 2003). This formula can be modified to be Eq. (3.2), yielding pressure in terms of mass flow rate.

\[
\dot{m} = \frac{p_o A}{\sqrt{T_o}} \sqrt{\frac{\gamma}{R}} \left( \frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)}
\]  

(3.1)

\[
P_o = \frac{m \sqrt{T_o}}{A} \left( \frac{\gamma}{R} \left( \frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)} \right)^{-\frac{\gamma}{\gamma-1}}
\]  

(3.2)
Since upstream temperature $T_o$, the gas constant $R$, and the specific heats ratio $\gamma$ are all relatively constant for air, one way to increase pressure is to decrease the orifice size $A^\prime$. If mass flow rate $m$ is constant, decreased cross sectional area will increase the upstream pressure $P_o$, which in this case is the tank pressure. Changing the area of the exhausting orifice would be cumbersome without the capability to adjust the diameter automatically.

A second method would be to increase the mass flow rate, while keeping the same size orifice. There are multiple ways to increase the mass flow through the tubes with facilities already in place. Without affecting equivalence ratio, the purge fraction and/or fill fraction can be increased. Higher filling ratios force more mass flow into the tube, and thus a higher mass flow trying to exhaust through the choked orifice. Engine frequency also has an effect on mass flow rate, since increased frequency increases the number of times the same amount of mass must be pushed into the tube. Other methods can be used to increase pressure, but for simplicity, increasing mass flow rate by these two methods was used. The pressure was varied over a large window to yield a complete description of how initial pressure affects the system.

To confirm that the tank orifice behaves similar to a choked orifice, pressure measurements were taken for different air flow rates. The choked orifice assumption is only valid at points where the pressure ratio across the orifice is $\frac{P_{in}}{P_{out}} \geq 1.893$, so a line is drawn at this location.
Figure 3.4: Pressure in tank compared to mass flow rate of air.

Figure 3.4 shows the relation between average air flow rate and tank pressure. The measured points mimic the slope of the calculated values above the choking pressure. Results vary slightly because there are losses and unsteadiness associated with the system. There are losses due to multiple surge tanks, lots of piping, and the valve orifices between the flow measurement point and the tank pressure measurement. Also, the flow is pulsated by the valves, and the choked flow assumption is based on a constant flow. The choked orifice equation of gas dynamics predicts pressures fairly well when just air is flowing, but this assumption is not valid during operation.
When the PDE is firing, tank pressure no longer depends solely on mass flow rate. Temperature changes drastically by the combination of the heat released during combustion followed by cool purge air between firing cycles. Other transient conditions include changing of species from combustion and pressure waves from combustion and valve motions. To measure pressure, a Sensotec (Model TJE, #060-0713-21TJA) pressure transducer was connected to the tank through a Chemiquip pressure snubber(Model # 25S). The pressure snubber damps flow oscillations to give a steadier reading, which not only helped readings converge on an average pressure value, but also protected the expensive transducer from large pressure oscillations that could cause damage. Another protective addition to the pressure transducer setup, was an approximately two and a half foot $\frac{1}{8}$" tube between the pressure snubber and the tank. This tubing prevents high temperatures of the tank from conducting into the transducer, which could affect readings and overheat the transducer. The tubing retards the pressure reading, but since an average value was the target, timing was not a factor.
Figure 3.5 is a schematic of the instrumented tube for hydrogen experiments. An 18” Shchelkin spiral is used for detonation of hydrogen. How detonable the fuel/air mixture is, among other things, determines the spiral length for each mixture. Each fuel, when detonated with air, requires a minimum spiral length to detonate, which was previously determined by Helfrich et al (Helfrich 2006). Helfrich determined that hydrogen only requires an 18” spiral, while ethylene requires a 36” spiral and aviation gasoline a 48” spiral. Switching the setup to testing for ethylene was a matter of
changing to a 36” spiral and shifting ion probes downstream to measure the DDT event. For aviation gasoline testing, the 48” spiral was placed in the tube and ion probes were once shifted further downstream to capture the DDT event.

As shown in Figure 3.3, two detonation tubes were used for these experiments. Only one detonation tube was used for measurements, and the other tube was there to help balance the system. A constant mass flow of fill and purge air are fed to the PDE, along with a constant fuel flow. When the valves close, the fuel and air flow feeding the valves continues. If the PDE system is operating with only one tube, every time the valves are closed to allow the tube to fire, the mixture will continue to flow, but with no flow out of the manifold, motion will decrease and pressure will build up behind the valves. If this buildup becomes substantial enough, the valves could be forced open, forcing detonable mixture into the tube and, if during the firing cycle, cause backfire. Also, each time the valves close and the air motion stops, the liquid fuel continues to pour into the feed line at a constant rate, making a fuel rich section of fill gases. Once the valves open, the air will surge forward at a higher volumetric flow rate causing a lean portion of fill gases to follow the rich portion. Since the values being measured are highly dependent on equivalence ratio, the uneven equivalence ratio would lead to large error in results. The second tube, firing 180° out of phase with the first, substantially decreases the time with no mass flow through the manifold. Less time with stopped flow results in less pressure buildup, and less of an equivalence ratio issue. Using four tubes would eliminate time with no flow through the manifold, but there is not enough space to put pressurizing tanks on all four detonation tubes. If each tube is not restricted in the same way, there will be more fill in tubes with less restriction, and
achieving higher initial pressures in the tube of interest would become very difficult due to the surge of air flow in the unrestricted tube. Further explanation of the air and fuel delivery systems is presented in Section 3.3.

Each tube has ion probes set in the flow path to measure combustion wave location. For this experiment, initial probe locations varied, but there was 6” from probe to probe. Each location is a hole drilled into the tube, with a 3/8”–24 UNF thread nut welded over the hole such that ion probes can be interchanged if a probe is broken.

![Figure 3.6: Autolite spark plug modified to be ion probe.](image)

Ion probes detect the free radical species created by a combustion event. The free radicals reach a high enough concentration in the intermediate combustion stages, to become electrically conductive plasma. Since a detonation or deflagration wave is driven by a combustion event, there will be an electrically conductive combustion zone moving with the wave. The ion probe (Figure 3.6) is a measurement device that detects the conductive part of the wave using voltage potential across a gap. This particular ion probe is a sparkplug (Autolite #4302) that has been rethreaded. The center post of the
spark plug is supplied 5 volts of electrical potential, and the threaded portion and tab are 
grounded to the tube. This configuration yields a voltage potential across the metal 
leads, which were placed in the path of the combustion wave. When the wave passes, 
the conductive plasma temporarily fills the gap and the voltage potential is shorted 
yielding a drop in the voltage signal. This particular ion probe setup has been 
developed and tested by (Zdenek and Anthenien 2004).

Figure 3.7: Ion Probe Signal.
A typical ion probe signal is shown in Figure 3.7. The voltage comes in at a steady value of roughly 4.5 V, and then reaches a point where a sudden drop is encountered. The voltage drop of the ion probe signal indicates that the combustion wave has reached the ion probe location and shorted the voltage gap. The wave then passes, and the voltage potential returns across the terminals, ready for another combustion wave measurement. Further explanation and use of this information is presented in Section 4.1.

In the DOHC cylinder head, there is a PCB102 (Model 232) pressure transducer to measure dynamic pressure. Dynamic pressure is different than absolute pressure. If the pressure is not dynamically loaded, it will not be detected. The PCB pressure transducer is a piezoelectric sensor that outputs dynamic pressures as a voltage that can be converted to pressure. When this piezoelectric core is compressed, it creates a voltage, but if it remains compressed, the voltage will slowly dissipate until it returns to a zero reading (Piezoelectronics). For this reason, the dynamic pressure transducer does not accurately measure static pressures. This sensor was designed specifically for measuring shock and blast waves, making it a perfect candidate to measure combustion. Use of the dynamic pressure trace is discussed in Section 4.1.

**3.3: Air and Fuel Support Systems**

The air and fuel support systems for the research PDE are described in the following paragraphs. Figure 3.8 shows a general schematic of the systems, with major components and flow paths.
Figure 3.8: Air and fuel support system schematic.
The air is fed to the engine from 3 large Ingersoll-Rand Pac compressors (#PA 300V), located outside of the test cell, with a maximum air capability of 3 kg/s, 6 lbm/s at 680 kPa, 100 psia. The air travels from the compressors, into a receiving tank with a main air valve separating the tank from the PDE test cell. When the main air valve is opened, the air flows through an air filter and into the main and purge lines. The flow is then controlled by a combination of a dome-loaded pressure regulator and choked orifice. The orifice is an interchangeable Flowmaxx Engineering sonic nozzle (Flowmaxx-Engineering) that, when choked, the mass flow rate is given by the gas dynamics Eq. (3.1). Where \( A^* \) is the constant throat area of the nozzle, which can only be changed, in this setup, with no air flowing. Other relatively constant variables are the upstream temperature \( T_o \), the gas constant \( R \), and the specific heats ratio \( \gamma \). This leaves only upstream pressure \( P_o \), to vary when the engine is operating.

Thus, by changing the pressure upstream of the nozzle, the mass flow rate into the system can be controlled. A dome loaded pressure regulator is located just upstream of the nozzle and is remotely controlled to set the pressure upstream of the nozzle.

Following the nozzle, a surge tank is used to prevent unchoking of the nozzle by pressure oscillations caused by the opening and closing of the valves.

Following the surge tanks, the purge and main airflows undergo slightly different operations. The purge flow has been measured and is ready to be used by the PDE, so the flow travels straight to the purge manifold. The main air flow is the first
part of the air and fuel mixture, and will need fuel injection prior to reaching the PDE fill manifold.

Gas fuels are delivered to the PDE through a system that is very similar to the air delivery system. The hydrogen is delivered to the fuel line from an outdoor hydrogen tube trailer. First, the fuel flows through a filter, then a similar dome loaded pressure regulator and choked nozzle setup. Then the fuel travels through a surge tank to damp out flow oscillations, and is injected into the air stream just after the air heater section. This location gives a sufficient amount of time for the fuel to disperse amongst the air and create a mixture. Ethylene was fed to the rig via gas cylinder, and went through the same lines as the hydrogen. Switching between the fuels was a matter of opening and closing a few valves and changing the constants in the flow measurement calculation. When the system is pressurized downstream of the nozzle, since the air and gaseous fuel nozzles are choked, the mass flow rates will not change. However, if the pressure increases and heat is not added, gases will compress similar to what is described by the ideal gas law, Eq. (3.3).

\[ pv = RT \]  

(3.3)

Where \( p \) is pressure, \( v \) is volume per unit mass, \( R \) is the gas constant, and \( T \) is the gas temperature. Since the gases compress downstream of the nozzle and the nozzle remains choked, the mass flow rate remains the same, but the volumetric flow rate will decrease. Two parameters that will be affected by this change are fill fraction and purge fraction. The fill/purge fraction is set by the user when the run specifics are input to the control interface (Figure 3.11). The fill/purge fraction represents the fraction of the tube volume that will be filled by the fill/purge gases. The system will
adjust the mass flow rate into the PDE using the fill/purge fraction, engine frequency, manifold temperature, and the assumption that the tubes are at atmospheric pressure. Since the gas is pressurized in the tubes the atmospheric assumption no longer holds. Thus, with temperature at a relative constant, twice the pressure in the tubes will result in half of the volume of the tube filled. This causes less fill of each tube. Higher fill fractions were used to better fill the portion of the tube with ion probes.

Following the gaseous fuel injection point, the air travels through a section where it can be heated. The heater was used for liquid fuel testing to accelerate the vaporization of liquid fuels. The vaporization time $t_v$ can be calculated using Eq. (3.4) (Kuo 1986, 379).

$$ t_v = \frac{\rho_{\text{liquid}} d_o^2}{8 \rho_{\text{gas}} \alpha \ln 1 + B} $$

(3.4)

Where $\rho_{\text{liquid}}$ is the density of the fuel, $d_o$ is the droplet diameter, $\rho_{\text{gas}}$ is the density of the vapor at the droplet surface, $\alpha$ is the diffusivity, and $B$ is the Spaulding transfer number. The vapor density is dependent on, among other values, the vapor pressure. Vapor pressure is the pressure exerted by the fuel, in absence of air, at a given temperature, and can be shown to increase with temperature (Cengel and Boles 2002). This increase in pressure causes an increase in density, which in turn decreases the time required for droplet vaporization. The droplet size is dependent on the spray nozzle, and droplet size distribution is not affected by increased air temperature. (Tucker 2005) showed that, in the present setup, without preheating air or fuel, residence time is simply too short to get an adequate and consistent vaporization of liquid avgas.
A subsequent effect of preheating the air is the temperature of the mixture after the fuel is vaporized. The effect of initial temperature on ignition time was shown in expression (2.22). If the mixture temperature is increased without varying other parameters, the exponential value will decrease, yielding a lower ignition time. So the increased air temperature will better vaporize the fuel prior to ignition and reduce ignition time due to increased mixture temperature. It is important to realize, that the air temperature before mixing is not equivalent to the mixture temperature. Since the fuel will vaporize, the latent heat of vaporization will play a role in reducing mixture temperature.

To calculate the temperature of the mixture after the aviation gasoline vaporizes, the first law of thermodynamics is used assuming no work or heat transfer.

\[
\dot{Q} - \dot{W} = \sum \dot{m}_{\text{out}} \left( h_{\text{out}} + \frac{V_{\text{out}}^2}{2} + g z_{\text{out}} \right) - \sum \dot{m}_{\text{in}} \left( h_{\text{in}} + \frac{V_{\text{in}}^2}{2} + g z_{\text{in}} \right)
\]  

(3.5)

Next, assuming negligible velocity or height change, we converge on a simple equation.

\[
0 = \sum \dot{m}_{\text{out}} \left( h_{\text{out}} + \frac{V_{\text{out}}^2}{2} + g z_{\text{out}} \right) - \sum \dot{m}_{\text{in}} \left( h_{\text{in}} + \frac{V_{\text{in}}^2}{2} + g z_{\text{in}} \right)
\]

\[
\sum \dot{m}_{\text{out}} h_{\text{out}} = \sum \dot{m}_{\text{in}} h_{\text{in}}
\]  

(3.6)

This equation is then expanded assuming constant specific heats for air and aviation gasoline through the vaporization process, and rearranged for the temperature of the mixture after complete vaporization.

\[
T_{mix} = \frac{\dot{m}_{\text{air}} C_{\text{p,air}} T_{\text{air}} + \dot{m}_{\text{avgas}} C_{\text{p,avgas}} T_{\text{avgas}} - h_{\text{vaporization}}}{\dot{m}_{\text{air}} C_{\text{p,air}} + \dot{m}_{\text{avgas}} C_{\text{p,avgas}}}
\]  

(3.7)
Where \( T_{\text{mix}} \) is the mixture temperature after complete vaporization of the fuel, \( \dot{m}_{\text{air}} \) and \( \dot{m}_{\text{avgas}} \) are the mass flow rates of air and aviation gasoline, respectively. \( C_{p,\text{air}} \) and \( C_{p,\text{avgas}} \) are the specific heats of the air and aviation gasoline, respectively, and \( T_{\text{air}} \) and \( T_{\text{avgas}} \) are the inlet temperatures of the air and aviation gasoline, respectively. \( h_{\text{vaporization}} \) is the enthalpy of vaporization for aviation gasoline. This value, and the specific heat value for aviation gasoline was assumed to be similar to that of gasoline. Numerical values for this calculation were taken from (Cengel and Boles 2002).

![Mixture Temperature After Fuel Vaporization](image)

Figure 3.9: Mixture temperature after aviation gasoline vaporization.
Aviation Gasoline was fed to the engine via 2 Greer-Olaer Model 30A – 2½ bladder accumulators that can displace 5 gallons of liquid fuel and have a pressure working range of 100psi to 1500psi. These bladder accumulators are shown in Figure 3.10 along with two nitrogen tanks used to pressurize the bladders.

![Figure 3.10: Aviation gasoline fuel supply.](image)

The fuel is pumped with the accumulator using high pressure nitrogen. It travels through a turbine fuel flow meter and up to the rig where it is sprayed by a combination of Delavan pressure atomizing nozzles (#46817-4, #27710-18, among others) into the
air just downstream of the heater section. The flow rate is controlled by the accumulator pressure and the spray nozzle types, but is measured using a Flow Technologies FT6 turbine flow meter. The nozzles, though difficult to change, can be switched to have higher or lower flow numbers, depending on the flow rate needed. Flow numbers are ratings given by the nozzle manufacturer and relate flow rate through the nozzle with square root of pressure (3.8).

\[
Flow \ Number = \frac{\dot{m}}{\sqrt{P}}
\]  

(3.8)

Where \( \dot{m} \) is the mass flow rate of liquid through the nozzle and \( P \) is the feed pressure to the nozzle. Due to the difficulty of changing the nozzles, the mass flow was changed by increasing and decreasing feed pressure whenever possible.

3.4: Control System

The functions of the rig are managed from a centralized control room. The main control unit is an in-house developed LabView based program. This program allows the user to input information like equivalence ratio, engine frequency, ignition delay, purge fraction, fill fraction, etc. The main operating screen of the program is shown in Figure 3.11. Through the help of many different electronic regulators and controllers, the engine can be tuned to the desired running condition. Many of the system components will adjust themselves automatically based on user specified values and system feedback. In addition to this program, there are back-up manual shutdown and safety systems.
3.5: Ignition Systems

Aside from the stock 12V DC automotive MSD Ignition system (PN 6215, DIS-4), two plasma ignition systems were employed. Both systems ignite the fuel air mixture with a much larger energy discharge than the MSD system. The MSD system supplies 3 sparks, each with a maximum 160-175 mJ of energy (MSD-Ignition). The three sparks ignite the fuel by heating a small local portion of the mixture and creating a
small amount of radicals through compound dissociation. The small portion then causes chemical kinetics to begin with the surrounding mixtures.

A plasma system runs on essentially the same concept, only with a much larger energy delivered in the spark. In this case, the typical discharge energy was $0.85J$ for the thermal plasma system and $0.95J$ for the transient plasma system. The systems were built by Ken Busby at Wright Patterson Air Force Base. Figure 3.12 shows a schematic of the circuit construction.

![Plasma ignition system circuit](image)

Figure 3.12: Plasma ignition system circuit.

This diagram is the basic skeleton of both the thermal plasma and transient plasma system. The major difference between the two is the thermal plasma system has an inductor between the capacitor and spark plug. This slows the current going through the circuit, causing a longer spark discharge. A list of components used for each system is presented in Table 3.1.
Table 3.1: Plasma circuit construction.

<table>
<thead>
<tr>
<th>Component</th>
<th>Thermal Plasma System</th>
<th>Transient Plasma System</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>9.41 nF (High Energy Corp)</td>
<td>1.3 nF (High Energy Corp)</td>
</tr>
<tr>
<td>D1</td>
<td>20 kV diode (HVCA)</td>
<td>60 kV diode (HVCA)</td>
</tr>
<tr>
<td>D2</td>
<td>32 kV diode (HVCA)</td>
<td>60 kV diode (HVCA)</td>
</tr>
<tr>
<td>E1</td>
<td>2 kW, -15 kV (Lambda ALE model 202A)</td>
<td>2 kW, -40 kV (Lambda ALE model 202A)</td>
</tr>
<tr>
<td>L1</td>
<td>0.714 mH</td>
<td>No Inductor</td>
</tr>
<tr>
<td>R1</td>
<td>400 MΩ</td>
<td>400 MΩ</td>
</tr>
<tr>
<td>R2</td>
<td>10 kΩ, 50 W</td>
<td>100 kΩ, 50 W</td>
</tr>
<tr>
<td>R3</td>
<td>20 kΩ, 50 W</td>
<td>100 kΩ, 100 W</td>
</tr>
<tr>
<td>R4</td>
<td>Autolite AR3934 spark plug</td>
<td>Autolite AR3934 spark plug</td>
</tr>
<tr>
<td>S1</td>
<td>Perkin Elmer GP-86 spark gap</td>
<td>Perkin Elmer GP-70 spark gap</td>
</tr>
</tbody>
</table>

All values were recorded by a LeCroy model 6050 oscilloscope that is remotely controlled from the control room. Figure 3.13 shows a typical trace recorded for the energy delivered to the spark plug for the thermal plasma system. Shown in Figure 3.14 is the power and energy delivered by the spark given in Figure 3.13. These values are calculated by the oscilloscope, using Eq.’s (3.9) and (3.10).

\[ P = IV \quad (3.9) \]
\[ E = \int P \, dt = \int IV \, dt \quad (3.10) \]
Figure 3.13: Voltage and current delivered to spark plug, thermal plasma system.
Figure 3.14: Power and energy delivered by spark plug, thermal plasma system.

The transient plasma system had slightly different results in terms of energy delivered in the spark plug. Figure 3.15 and Figure 3.16 show the current, voltage, power, and energy delivered by the transient plasma system.
Figure 3.15: Voltage and current delivered to spark plug, transient plasma system.
Figure 3.16: Power and energy delivered by spark plug, transient plasma system.

One variation in the ignition systems is the Paschen law, which states that as pressure increases the voltage required to breakdown an air gap increases. Figure 3.17 shows the Paschen curve, which is a plot of voltage required to break down a gap compared to pressure level multiplied by gap size (x).
Thus, as higher initial pressures are tested in the tube, more voltage is required to break down the gap of the Autolite racing spark plug. Since energy delivered from the spark is proportional to voltage (Eq. (3.10)), the energy delivered in the spark will increase slightly with higher initial pressures.

### 3.6: Data Collection Equipment

All data is captured and managed in the control room. The LabView based control for the engine takes low speed data (2Hz), while a separate computer handles the high speed data (0.5-5 MHz range). The low speed data contains values that
characterize the running conditions of the engine, such as temperature, air flow rate, fuel flow rate, and frequency. The low speed data is recorded through a data acquisition system comprised of a variation of National Instruments SCXI signal conditioning and switching platforms (1001, 1303, 1314, 1321, 1324, 1325, and 1326).

Ion probe signals, head pressures, and spark traces are the kind of data recorded at the high speed data rate of 0.5 MHz-5MHz. The data found at the high speed rate are needed to find the numerical results in these experiments. The high speed data is recorded using a different LabView interface known as *Online Wave Speed*. The high speed computer is equipped with three National Instruments BNC-2110 input/output connector blocks, plugged to a NI PCI-6110 input board. This system is capable of up to 16 channels of data, taken simultaneously with a sampling rate up to 5 MHz.

### 3.7: Data Collection Procedures

A typical data set for each run in this analysis included the spark trace, head pressure, 5 ion probe voltage traces, and the tank pressure from the tube of interest. The head pressure trace was used for calculation of the ignition time. The tank pressure was taken as the initial pressure of the tube and the ion probes allowed for calculation of wave speeds. The data rate for this experiment was 1MHz, with a sample window of 500,000 points, yielding 0.5 seconds of data per set. Three to ten data sets were taken for each run condition, and since the frequency of the engine varied between 10 and 15Hz, this yields at least 15 firing cycles.

One major goal of the research was to find the dependence of ignition time, DDT time, and DDT distance on pressure. Two ways to vary pressure are, as
previously discussed, increase mass flow rate into the tube or decrease exhausting orifice size. Shown in Table 3.2 is a sample of how the major control interface input parameters varied for aviation gasoline. Other parameters remained constant during each of these tests. There are more runs taken with stoichiometric mixtures than without to create better resolution of a plot where only initial pressure varies.

<table>
<thead>
<tr>
<th>Avi prevention Parameters</th>
<th>Equivalence Ratio</th>
<th>Fill Fraction</th>
<th>Purge Fraction</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>0.8</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>0.8</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>0.8</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>0.8</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>10</td>
</tr>
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<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
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<td>1.2</td>
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<td></td>
<td>1.3</td>
<td>1.0</td>
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<td>0.8</td>
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<tr>
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<tr>
<td></td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3.2: Variation of run conditions for aviation gasoline.

Different fuel studies follow the same variation of parameters as the aviation gasoline experiments, with the exception of equivalence ratio. As can be seen in Table 3.2, aviation gasoline was varied over equivalence ratios 1.0-1.4 with increments of 0.1.
The equivalence ratio range tested varies based on the fuel, and was selected using the results of (Helfrich 2006). For this research, equivalence ratios 0.7-1.7 for hydrogen, 1.0-1.5 for ethylene, and 1.0-1.3 for aviation gasoline are studied. Since all equivalence ratios presented in (Helfrich 2006) are not needed to prove the pressure dependence, only a portion of the detonable range was considered for each fuel. The ranges selected contain the minimum ignition times and a few points to each side such that the trend of the curve could be reproduced. Also, the different range sizes were used to keep the range of DDT distances close to one another, to prevent the need to change spiral lengths for the same fuel.

Each run was carried out in a similar manner to try to reduce error as much as possible. Once the experimental setup was completed, a test run was taken to make sure that sensors support systems were working properly. Once the engine was working properly, a set of parameters, such as the ones listed above, are input to the control interface. The air flow rates are calculated by the program, and the dome loaded pressure regulator is used to adjust the flow to within 1% of the calculated value. Then, once the air flow was stable, the spark system began discharging, and the fuel supply began to flow. For gaseous fuels, the fuel flow gradually increases as the dome loaded pressure regulator increases the pressure upstream of the choked orifice. Once the equivalence ratio reaches within 0.01 of the desired value for 2 seconds, the desired data sets were taken and saved. The reason for waiting two seconds is to allow time for the fuel that is being measured at the choked orifice to make its way through the system to the detonation tube. As soon as the last data point is taken, the fuel valve was closed and the equivalence ratio rapidly falls until it reaches zero. The spark is then shutoff
and air continues to flow to cool down the apparatus. Once the temperature of the tank falls below 200 °K, the next run can begin. The cooling cycle allows for a common starting place for each of the runs.

Aviation gasoline testing was very similar to the gaseous fuel run procedure. Differences in the test procedure came about because liquid fuel has a different delivery system. The air was preheated to 220°F to accelerate aviation gasoline vaporization. This preheating was the first step in the testing process, and once the temperature of the air stabilized at 220±10°F, the spark was turned on followed by the fuel. The fuel delivery system had to be manually adjusted to the proper flow rate such that the equivalence ratio was within 0.01 of the desired value. Then, after a 2 second wait, the data sets were taken one after another, and once the final set was recorded, the fuel was turned off. The equivalence ratio then falls to zero, after which the spark is turned off. The air flow then cools the system until the tank temperature fell below 250°F, and then the next test began.

There were a lot of issues with backfire in the system caused by the elevated pressures, so the runs were kept as short as possible. It is believed that since higher pressure causes higher temperature, the elevated pressure experiments allowed for materials to heat up beyond the ignition temperature of the fuel air mixtures and cause ignition during the fill cycle. To better cool the tube and its components, large purge fractions were used, but the backfire problem was not completely resolved. This is why the equivalence ratio was only allowed to settle for 2 seconds, and as few as 3 data sets were taken for some runs. Backfire was more of an issue in ethylene and hydrogen
mixtures, than in aviation gasoline mixtures. This was because of the easy ignitability of the ethylene and hydrogen as compared to aviation gasoline.

3.8: Chemkin Analysis

Aside from the experimental work explained, a computer analysis was done to model the beginning of the PDE combustion event. Chemkin is a commercially available combustion kinetics code (Kee, et al. 2006). This code can model a plethora of different combustion situations to give further insight into how combustion species behave during the combustion process. Chemkin’s basic operation is to solve the finite rate kinetic equations for each elementary reaction in the combustion event. The finite rate kinetic equations are similar to Eq. (2.4). Chemkin uses many different methods to solve the variation of species in a combustion event, and detailed information about Chemkin’s operation is available in (Kee, et al. 2006).

For this research, Chemkin was used to gain better understanding about the ignition process in the PDE. A 0-D reactor model was used, which means that no flow consideration are presented, just the finite rate kinetics of the mixture are modeled. Once the model finishes solving the kinetics, plots can be constructed that show species concentrations, temperatures, densities, pressures, etc. all varying with time. In order for the reactor to be able to solve the equations, at least one variable must be constrained. No variable is truly constant, thus constant pressure and constant volume situations were examined. The model was only used to determine ignition time, thus any species variation or behavior following ignition will be different since DDT is such a transient process.
The PDE is ignited using a spark, which Chemkin does not have the ability to directly model. The sparking event is not entirely thermal, as it also creates some dissociation of compounds into radical species. The OH ion is a major radical that has been shown to be present during the combustion process. This is why its production was used to define ignition when validating the PCB pressure transducer method (Tucker 2005). So to attempt to capture the process of spark ignition, initial temperature and initial OH species concentration were varied. To determine the ignition system combination, the trend of the ignition time as compared to pressure for the stoichiometric equivalence ratio had to match. For other equivalence ratios, the temperature found for the stoichiometric condition was used, and the OH species was varied to line up the estimated atmospheric ignition times with the measured values. The notion behind this variation method was that the sparking energy has minimal change through the different tests, resulting in similar heating of the affected volume, and the change in mixture results in different species concentrations in the effected area, giving reason for OH production to vary. Thus, values that were matched by variation of parameters were all the stoichiometric ignition times, and the atmospheric ignition times for other equivalence ratios.

Criteria for mixture ignition must be similar to that used in the PDE. Ignition in the PDE was found using the slope of the pressure curve, and this method was confirmed using OH species imaging. Wanting to remain consistent with the measurement method, ignition time was defined as the inflection point of the OH species, which represents the point of greatest OH production. As Figure 3.18 shows, this corresponds with the time of the inflection point of temperature. This method is a
similar method to the PDE measurement, and can be used for both constant pressure and constant volume analysis. All modeling was done to attempt to mimic the behavior of the MSD ignition system.

Figure 3.18: Temperature and OH species variation for modeled iso-octane combustion.

To model each different combustion case, Chemkin requires the input of the Arrhenius rate constants that were described in Eq. (2.5). These constants are experimentally determined for each elementary reaction. Also, thermodynamic data is compiled for all species. Together these constants create a Chemkin mechanism. The
mechanisms used were developed in the Lawrence Livermore National Laboratories (LLNL), and have been tested in multiple situations. LLNL manages a website that allows others to use their mechanisms for a multitude of different fuels (LNLL 2008). LNLL offers mechanisms for hydrogen, ethylene, and iso-octane, among others. The iso-octane mechanism was used to represent aviation gasoline, as iso-octane is a benchmark fuel that behaves similarly to gasoline. This mechanism involves 857 species, and 3606 elementary reactions and the rate data is credited to (Curran, et al. 2002). This requires a large amount of computing time to formulate results, and since aviation gasoline requires up to $10\text{ms}$ to ignite, the maximum time step was set to $10\mu\text{s}$, yielding ignition times to the nearest ten microseconds. The ethylene mechanism had 155 species and 689 elementary reactions, thus the resolution was increased to yield ignition times to the nearest microsecond. Hydrogen had only 10 species and 21 reactions, so microsecond resolution was once again used. The ethylene mechanism is credited to (Marinov, et al. 1998), and the hydrogen mechanism is credited to (O’Connaire, et al. 2004).
In this chapter, the data analysis procedures are outlined in detail. The statistical methods that were used are explained and justified. The uncertainty analysis is presented, starting with elemental measurement uncertainties, and then systematic uncertainties that contribute to errors in the results. Lastly, a short overview of some uncertainties that were not numerically accounted for, and likely added to the random uncertainty found with the data.

4.1: Determination of Ignition and Ion Probe Times

As previously stated, each data set contained a spark trace, five ion probe traces, tank pressure and head pressure. The same data was collected for each run and each data set looked similar to the data set shown in Figure 4.1.
The first step in the analysis of the data sets was to calculate ignition times for each cycle. Ignition time is the time from when the spark discharges, to when a flame is first established. To extract this critical value, the PCB dynamic pressure transducer trace was used. Ignition time is assumed to be the location where the PCB signal first reaches a slope of $\frac{5V}{s} \frac{5000 \text{ psi}}{s}$. This measurement method was confirmed by (Tucker 2005) to yield ignition times 10-15% faster than OH imaging.

Ion probe times were the other critical values that are needed for analysis. An ion probe signal is shown in Figure 3.7 and the ion probe time is the time at which the
signal makes a sharp drop. As previously discussed, this drop represents the passing of a combustion wave. Each cycle will have five ion probe times, with five corresponding ion probe locations.

Finding ion probe and ignition times can be done by picking points off a graph, but to accelerate the analysis process and establish analysis repeatability, a C++ program was used to find these values automatically. Capacitors for the spark plugs were given 2 milliseconds to charge before the spark discharge. Thus, the trace stays at zero voltage, spikes to roughly 5 volts, holds for 2 milliseconds, and drops back to zero voltage. Since the discharge begins at the drop in voltage, this is the starting time for measurement of ignition time and ion probe times. The C++ program averages the flat line of the spark trace, finds the sharp spike in signal by finding the first point to go above a threshold for over 500 points. Then the program looks for the signal to fall below the same threshold after the 2 millisecond charge cycle, and stay below the threshold for 500 points. The time of the first of those 500 points is then recorded as the spark discharge time. This process is repeated along the entire spark trace to locate each of the firing cycles. The time of the spark discharge is the start of the combustion process, and ignition times and ion probe times are given with zero representing the spark discharge time.

Once the spark discharge is located, the program starts analyzing other traces from that point forward. The head pressure trace is first run through a Savitsky-Golay filter to smooth the curve (Parker and Schauer 2003). This eliminates most of the noise in the signal, giving a relatively smooth curve. Figure 4.2 shows a pressure trace before and after the filter.
The average slope of the first 600 points of the filtered pressure trace is calculated with the least squares approximation (Faires and Burden 2003). If the slope is less than $5V/s$, the program shifts the 600 point window forward by 1 point. The average slope is again calculated, and the process repeats moving forward one point at a time. Once a slope of $5V/s$ is achieved, the midpoint of the 600 point interval is recorded as the
ignition time. Because of noise issues, a 2000 point interval was used for aviation gasoline analysis.

To find ion probe times, the C++ program takes an average of the first 1000 points of each ion probe curve. Then the program follows each ion probe curve (Figure 3.7) to see when the values fall below a threshold value for at least 500 consecutive points, similar to the method used to find the spark. The threshold value was set as $0.01 V$ below the average charged ion probe value. The very first point of the 500 consecutive points below the average is recorded as the ion probe time.

**4.2: Determining Wave Speeds**

The next step to extract results is to determine average wave speeds between two probes. Eq. (4.1) is used, where $\Delta x$ is the distance between probes and $\Delta t$ is the difference in probe times.

$$u_{avg} = \frac{\Delta x}{\Delta t}$$

$$\Delta x = x_{probe 2} - x_{probe 1}$$

$$\Delta t = t_{probe 2} - t_{probe 1}$$

Eq. (4.1)

It is important to remember that this is an average wave speed that is calculated, and the actual velocity profile is not known. This will be a source of error that is examined thoroughly in Section 4.5.

C-J wave speeds were also determined this way, combined with the understanding of the phenomena. As described in Section 2.2, the Chapman Jouguet (C-J) speed is the velocity that a detonation wave converges to once it reaches a self-sustained state. Reaching this velocity is the criteria used for this study as achieving
detonation. To find the C-J speeds, 5 ion probes were placed in the detonation tubes just past the location where detonation is achieved. Since the detonation wave will converge on the C-J velocity, multiple average wave speeds were calculated in a row to find repeating velocities. Once the wave velocity remains relatively constant for 2 or more intervals, the average wave speed over those intervals was accepted as the C-J speed. Figure 4.3 shows wave speeds that were measured at different distances from the head, in a detonation tube. As expected, the values peak and drop down to the C-J value, where it stabilizes.

Figure 4.3: Wave speeds measured to calculate C-J speed.
C-J speeds have shown to vary with, among other things, equivalence ratio, initial pressure, and mixture composition. C-J speeds were calculated for each mixture at all of the equivalence ratios tested and at multiple pressures. The results are presented in Section 5.1, and are compared to those predicted in the detonation database (Kaneshige and Shepherd 1997). The calculated wave speeds were also used in the analysis to find DDT times and distances, which is explained in Section 4.3.

4.3: Determining Deflagration to Detonation Transition Times and Locations

The total detonation time is the time from spark discharge to when the wave speed first reaches the C-J speed. The average wave speed was assumed to be the wave speed at the center of the time interval over which it was calculated. A series of ion probes were placed on the tube, so several average wave speeds were calculated, along with their corresponding times. Interpolation for the time where the wave speed first reaches the CJ speed yields the time required to achieve detonation. DDT time is the time from ignition to detonation, so the ignition time was subtracted from the total detonation time to get the final result. DDT distance is found similarly with the interpolation yielding the location where C-J wave speed is first reached. Since the flame starts at the beginning of the tube, there is no need to subtract any type of distance from the total distance to detonation.
\[ t_{DDT} = \frac{t_B - t_A}{V_B - V_A} V_{CJ} - V_A + t_A - t_{\text{Ignition}} \]

\[ t_A = \frac{t_1 + t_2}{2} \]

\[ t_B = \frac{t_2 + t_3}{2} \]

\[ x_{DDT} = \frac{x_B - x_A}{V_B - V_A} V_{CJ} - V_A + x_A \]

\[ x_A = \frac{x_1 + x_2}{2} \]

\[ x_B = \frac{x_2 + x_3}{2} \]

Eq. (4.2) is used to calculate DDT time \( t_{DDT} \), where \( t_1, t_2, \) and \( t_3 \) are ion probe times of three successively places ion probes. The velocities \( V_A, V_B, \) and \( V_{CJ} \) are the average velocity calculated between ion probes one and two, average velocity calculated between ion probes 2 and 3, and the C-J velocity of the current mixture, respectively. \( t_{\text{Ignition}} \) is the ignition time and is determined by PTFinder. Eq. (4.3) is used to calculate DDT distance, where \( x_1, x_2, \) and \( x_3 \) are location of three successively placed ion probes and the velocities are the same as those defined for Eq. (4.2).

To calculate these values in an efficient and reliable manner, the ignition times and probe times determined by PTFinder were copied to an excel spreadsheet. Tank pressure, fuel type, ion probe locations, C-J Speeds, and equivalence ratio were also input to the spreadsheet. The spreadsheet calculates wave speeds, then searches for the first wave speed above or equal to the C-J speed. Then applies the linear interpolation method just described to yield a single value. The method for determining the
detonation distance is explained graphically in Figure 4.4. Changing the x-axis values to ion probe times, the detonation time is found similarly.

Figure 4.4: DDT distance calculation method.

4.4: Data Distribution and Statistical Analysis

As previously discussed, data was taken for a minimal 15 firing cycles for every data point of interest. This results in several data points that need to be reduced to one
value. To get an idea of the distribution that best defines the data as a whole, a histogram of two of the larger data sets is shown in Figure 4.5.

![Figure 4.5: Histogram of ignition time data sets.](image)

The data sets above are out of phase because the data sets are from two different pressures. Each data set mimics the most widely used statistical distribution, the normal distribution.

The normal distribution is based on the central limit theorem, which postulates as a random experiment is repeated and the number of data points becomes large, a
histogram of the values will slowly converge a bell shaped curve (Montgomery and Runger 2003). The bell curve is centered at the mean value of the data. Confidence intervals are setup based on variation of the data. The mean of the data \( \bar{x} \) was calculated using Eq. (4.4), and the standard deviation \( \sigma \) was calculated using Eq. (4.5).

\[
\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{4.4}
\]

\[
\sigma^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1} \tag{4.5}
\]

Where \( n \) is the total number of data points and \( x_i \) is the value of an individual data point. The standard deviation is the positive square root of the \( \sigma^2 \) equation. The standard deviation is used to determine the confidence interval. A 95% confidence interval represents an interval in which there is a 95% chance the data will fall. Figure 4.6 shows a normal distribution bell curve, where the function plotted is the probability that the horizontal axis value will be the result.
The 95% confidence interval is from 2 standard deviations less than the mean, to 2 standard deviations more than the mean.

4.5: Quantitative Uncertainty

Uncertainty is the amount of error that is thought to be in a result (Coleman and Steele 1999). Uncertainty analysis is a method that is used to calculate this error, to give further meaning to the error bars that are placed on data points. A systematic uncertainty analysis was performed on all values used in this experiment, using the methods outlined in Coleman’s book. The total uncertainty in a final result is a
combination of systematic uncertainty, and random uncertainty. The random uncertainty \( P_r \) for an experiment such as this one is twice the standard deviation of the data set. This value was already calculated in the previous section, to find a 95% confidence interval. The systematic uncertainty \( B_r \) results from measurement capabilities. The total uncertainty \( U_r \) is calculated from these two uncertainties using Eq. (4.6).

\[
U_r = \sqrt{B_r^2 + P_r^2}
\]  

(4.6)

The random uncertainty is determined with the statistical methods explained in Section 4.4, so calculation of the systematic uncertainty is examined in this section. The systematic uncertainty is found by taking the uncertainty on an elemental level \( B_i \), and calculating the error it contributes to the result. An example of an elemental uncertainty is calibration of a pressure transducer to be within 1% of the actual pressure. In some cases there is more than one elemental error in one measurement such as an error from the measurement device, and an error in the recording device. These uncertainties were combined using Eq. (4.7), where \( M \) is the total number of errors being combined.

\[
B_i = \sqrt{\sum_{k=1}^{M} B_{ik}^2}
\]  

(4.7)

Once all elemental uncertainties are determined, propagation of the error through the equations can be tracked with Eq. (4.8).

\[
B_r = \sqrt{\sum_{i=1}^{J} \left( \frac{\partial r}{\partial x_i} \right)^2 B_i^2}
\]  

(4.8)
Where $r$ is the equation used to calculate the final result, each $x_i$ is a variable that has error and is used in the calculation, $B_i$ is the elemental error in $x_i$, and $J$ is the total number of variables with elemental error.

To formulate the $B_r$ values, all of the elemental uncertainties of the setup were collected from the system. The first sensor that was examined was the ion probe. The ion probe was used to detect the combustion wave at different points along the length of the detonation tube. The response time of the ion probe was shown by (Zdenek and Anthenien 2004) to be $0.1\mu s$, resulting in an elemental uncertainty of $\pm 0.05\mu s$. The computer data recording rate was $1MHz$, measuring one data point every microsecond and creating an elemental uncertainty of $\pm 0.5\mu s$. Location of each ion probe was measured to the nearest $\frac{1}{16} " 1.59 mm$, resulting in an elementary location uncertainty of $\pm \frac{1}{32} " 0.79 mm$. Elemental uncertainty is also present in the magnitude of the ion probe voltage, but will be ignored since the measurement of interest is the time of the drop in voltage and not the magnitude.

Another sensor used for numerical results was the PCB pressure transducer. Measuring the head pressure, data was taken every microsecond, resulting in an elemental uncertainty of $\pm 0.5\mu s$. The PCB manufacturer specifies that the PCB pressure transducer responds within a microsecond, and measures within $0.1\%$ of the pressure. Resulting in elemental uncertainties of $\pm 0.5\mu s$ for probe response and $\pm 0.1\%$ of the pressure (Piezoelectronics). Another elemental uncertainty arises from the computer data collection program Online Wave Speed. The computer records the
data with a resolution of 4000 points over the selected voltage range. Since the voltage range of the pressure transducer is from $-1V$ to $1V$, this results in a recording range of $2V$ and an increment of $0.5mV$. So an elemental uncertainty of $\pm 0.25mV$ is introduced.

A Sensotec TJE model pressure transducer was used to measure the tank pressure, which is used as the initial pressure in the detonation tube. This transducer is capable of measuring within 0.1% of pressure. This results in an elemental uncertainty of $\pm 0.1\%$ for the pressure measurements. Computer resolution also plays a part in the uncertainty, with a range of $10V$, the 4000 possible measurement points resulted in an elemental uncertainty of $\pm 1.25mV$. To add to this, the pressure trace was rounded to the nearest $5mV$, resulting in a single value and $\pm 2.5mV$ elemental uncertainty. A pressure snubber and a length of small tubing separate the pressure transducer and the tank. Pressure loss through tubing is dependent upon velocity of the flow, among other variables (Fox, et al. 2004). Since mass motion in the tube is minimal, the pressure loss in the tubing is minimal and can be neglected. The pressure wave will travel through the tube at the speed of sound, thus the reading time is delayed. The pressure snubber reduced the sharp oscillations that would come as a result of shock waves, but retains the average pressure in the tank. Since an average pressure is used, there is minimal uncertainty introduced by the addition of the snubber and tubing and it will be neglected. The final source of elemental uncertainty in the pressure measurement results from signal amplification. A Preston 8300 XWB signal conditioner was used to amplify the incoming signal 200 times and filter noise above 1000Hz. The error published by Preston for the gain function of the signal conditioner is $\pm 0.01\%$ (Preston).
Other uncertainties from the amplifier result in a phase shift from the filtering option, but as previously discussed, the value is averaged and phase does not matter, so this elemental error will also be ignored.

Equivalence ratio was one of the major parameters varied during testing. After it was input to the control interface, desired flow rates for fuel and air were calculated by the LabView program. The flow rates were adjusted to maintain an equivalence ratio within 0.01 of the desired value. Thus elemental uncertainty of the equivalence ratio from the control operation is ±0.01. Of course there are other elementary uncertainties present in the flow measurements sent to the control interface. Each of the critical nozzles used for air or gas flow is manufactured to yield flow values within 1% of the measured value (Flow-Dyne, Flowmaxx-Engineering). The turbine flow meter used to measure the flow rate of aviation gasoline has a manufacturer specified accuracy of within 0.05% of the measured value (Flow-Technology 2007). So elemental uncertainty in gaseous flow rates is ±1.0%, and in aviation gasoline flow rate is ±0.05%. A critical nozzle is used to measure flow rate, because once the flow is choked, the flow depends entirely on the pressure upstream of the nozzle. Thus, the final elemental uncertainty results from the pressure measurement upstream of the nozzle that is converted into the flow rate through Eq. (3.1). The transducer used to measure pressure at this point is a Sensotec model TJE sensor and contributes ±0.1% of elemental uncertainty in the measured upstream pressure.

For the calculation of DDT time and distance, there are elemental errors introduced through assumption. As explained in Section 4.3, to converge on a location in both space and time for DDT, the calculated average wave speeds were assumed to
be at the center of the interval over which they were calculated. While this is a logical assumption, it can be shown that this average wave speed means only that the wave speed was achieved at some point in the interval. Since the interval is $0.152\ m$ 6", this results in an uncertainty in wave speed location of $\pm0.076\ m$ 3". For wave speed time, the uncertainty will be half of the time elapsed over the interval.

<table>
<thead>
<tr>
<th>Measurement Device</th>
<th>Elemental Uncertainty</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Probe</td>
<td>$\pm 0.5\ \mu s$</td>
<td>Probe Response Time</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.5\ \mu s$</td>
<td>Computer Sampling Rate</td>
</tr>
<tr>
<td></td>
<td>$\pm \frac{1}{32}''\ 0.79\ mm$</td>
<td>Probe Location</td>
</tr>
<tr>
<td>PCB Pressure Transducer</td>
<td>$\pm 0.05\ \mu s$</td>
<td>Transducer Response Time</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.5\ \mu s$</td>
<td>Computer Sampling Rate</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.1\ %$</td>
<td>Pressure Accuracy</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.25\ mV$</td>
<td>Computer Resolution</td>
</tr>
<tr>
<td>Sensotec Pressure Transducer</td>
<td>$\pm 0.1\ %$</td>
<td>Pressure Accuracy</td>
</tr>
<tr>
<td></td>
<td>$\pm 1.25\ mV$</td>
<td>Computer Resolution</td>
</tr>
<tr>
<td></td>
<td>$\pm 2.5\ mV$</td>
<td>Rounding</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.01\ %$</td>
<td>Preston Filter Gain</td>
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<tr>
<td>Equivalence Ratio</td>
<td>$\pm 0.01$</td>
<td>Control Operation</td>
</tr>
<tr>
<td>Gaseous Flow</td>
<td>$\pm 1.0\ %$</td>
<td>Mass Flow Accuracy</td>
</tr>
<tr>
<td></td>
<td>$\pm 0.1\ %$</td>
<td>Pressure Transducer Accuracy</td>
</tr>
<tr>
<td>Aviation Gasoline</td>
<td>$\pm 0.05\ %$</td>
<td>Mass Flow Accuracy</td>
</tr>
<tr>
<td>Wavespeed</td>
<td>$\pm Time\ Interval/2$</td>
<td>Mid-Interval Assumption</td>
</tr>
<tr>
<td></td>
<td>$\pm 3''\ 76.2\ mm$</td>
<td>Mid-Interval Assumption</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of elemental uncertainties.
The elemental uncertainties listed above were then put through Eq.’s (4.7) and (4.8), to calculate the systematic uncertainty of the results. The first calculation was for wave speed uncertainty. Using elemental uncertainties for ion probe times and locations, the systematic uncertainty can be calculated. The result is dependent on the wave speed, but for a speed of $1800\;\text{m/s}$, the systematic uncertainty is

\[ \pm 15.03\;\text{m/s} \quad 49.31\;\text{ft/s}. \]

Systematic ignition time uncertainty develops in a variety of ways. PCB head pressure is used to determine the ignition time, so elemental errors from the PCB pressure transducer were expanded through the least squares linear regression used by PTFinder. The calculation requires use of an actual data set, so the systematic uncertainty was found to be the highest in hydrogen calculations where a smaller averaging window was used. The maximum error in the slope of the pressure curve was $\pm 0.004\;\text{V/s}$, and when following the calculated slope, resulted in a systematic uncertainty of $\pm 0.5\;\mu\text{s}$. This is the uncertainty in the slope of the linear regression, assuming that the slope at the center of the interval is equivalent to the regression value.

To finalize the uncertainty analysis of ignition times, the accuracy of the PTFinder analysis method was tested. Multiple runs with minimal standard deviation were tested for each fuel. Each of the runs was loaded into a graphical processing program and the point where the pressure trace slope reached $5\;\text{V/s}$ was selected. The point selection process was done multiple times for each point to determine the
uncertainty in the manual selection process. Selection of ignition time via this method was determined to yield results within $50\mu s$, resulting in an uncertainty of $\pm 50\mu s$.

The ignition times were then compared to those found by PTFinder. The results showed that the ignition times found for hydrogen with a 300 point window were within $10\%$ of the selected values, and most results within $5\%$ of the selected values. Analysis on ethylene data showed that values were within $5\%$ of the graphically determined result, and aviation gasoline analysis showed that a 2000 point window yields results within $5\%$ of the graphically measured values. Using a representative ignition time of $800\mu s$, the systematic uncertainty of ignition time for hydrogen was determined to be $\pm 94\mu s$. Likewise, using an ignition time of $3000\mu s$, the systematic uncertainty of ethylene ignition time was determined to be $\pm 158\mu s$. Lastly, with a representative ignition time of $7000\mu s$, the systematic uncertainty of aviation gasoline ignition time was determined to be $\pm 354\mu s$.

DDT distance and time are two other results that both contain systematic uncertainty. For DDT time, the calculation done by Eq. (4.2) was affected by elemental uncertainties of the ion probe times, ignition time, wave speeds and wave speed time location. The wave speed and ignition time uncertainties were calculated by the methods in the previous two paragraphs. This uncertainty is also a function of the wave speeds that are used to interpolate the solution. Since these speeds vary, the representative case used was $1400m/s$ before detonation onset, $2100m/s$ after detonation onset, and a C-J speed of $1800m/s$. This case results in one of the largest errors, in the DDT calculation, of the values that were measured. Combining the errors
of ignition time, wave speed, and those in Table 4.1, the systematic uncertainty for DDT time was calculated as \( \pm 113 \mu s \) for hydrogen, \( \pm 170 \mu s \) for ethylene, and \( \pm 360 \mu s \) for Aviation Gasoline. Calculation for DDT distance was done with the same representative case in mind, and when all values are combined, the systematic uncertainty is \( \pm 0.105 m \) 4.126".

Initial pressure and equivalence ratio were the parameters varied during testing and uncertainty of these values is also important. The equivalence ratio is determined by Eq. (2.7), and is calculated using the stoichiometric ratio and the mass flow rates into the detonation tube. Using the elemental uncertainties outlined in the equations presented, the systematic uncertainty of the equivalence ratio was calculated as \( \pm 0.017 \) for gaseous fuel testing and \( \pm 0.015 \) for aviation gasoline testing. Pressure was measured in the tank with the Sensotec model TJE pressure transducer. The elemental uncertainties listed combine together to give a systematic uncertainty of \( \pm 4.8 kPa \) 0.70 psi for the initial tube pressure reading.

The elemental uncertainties have been collected at each stage of the measurement and analysis process, then propagated through the analysis steps to result in systematic uncertainties. A summary of the systematic uncertainties is presented in Table 4.2.
### Result Systematic Uncertainty

<table>
<thead>
<tr>
<th></th>
<th>Ignition Time*</th>
<th>DDT Time*</th>
<th>DDT Distance*</th>
<th>Equivalence Ratio</th>
<th>Initial Pressure</th>
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<tr>
<td></td>
<td>Hydrogen</td>
<td>Ethylene</td>
<td>Aviation Gasoline</td>
<td>Hydrogen</td>
<td>Ethylene</td>
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<td></td>
<td>±94 $\mu s$</td>
<td>±158 $\mu s$</td>
<td>±354 $\mu s$</td>
<td>±113 $\mu s$</td>
<td>±170 $\mu s$</td>
</tr>
<tr>
<td></td>
<td>±0.105 m</td>
<td>±4.126&quot;</td>
<td></td>
<td>±0.017</td>
<td>±0.017</td>
</tr>
<tr>
<td></td>
<td>±4.8 kPa</td>
<td>±0.70 psi</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

*Representative values

Table 4.2: Summary of systematic uncertainties for results.

It is important to note that many of these results were calculated from “representative” values. “Representative values” are conditions chosen that are similar to the majority of data taken, and have a slightly higher error value, such that the error in measurement is not understated. The systematic uncertainty was combined with the random uncertainty for each data point to comprise the error bars seen on the plots presented in the results chapter.
4.6: Qualitative Uncertainty

Aside from the numerical uncertainty analysis, there are several issues that introduce error that cannot be quantified. This error will likely be absorbed into the random error found within the data sets. One possible source of an error like this is the aviation gasoline mixture. Aviation gasoline is a mixture of multiple hydrocarbons that can vary between batches. Different chemical compositions will result in different combustion characteristics. Aside from the chemical makeup of the aviation gasoline, the air was preheated to aid in the vaporization of the aviation gasoline as shown in Section 3.3. It is possible that some of the liquid fuel did not fully vaporize before it filled the detonation tube, altering the mixture in the tube. This could be one source for the large confidence intervals for aviation gasoline experiments as compared to those of ethylene and hydrogen.

Another introduction of error comes from the pressure measurement location. Figure 4.7 shows a plot of head pressure as compared to the tank pressure measurement for just air flowing through the system, where zero represents closing of the main valves.
The pressure drops slightly because of the expansion waves from the valves closing, but then rebounds from compression waves returning from the end of the tube. This trace is similar to the pressure measured by (Knick 2006). The maximum ignition delay was 4\(ms\) used for aviation gasoline testing, and was a consistent value used through testing. Hydrogen and ethylene had a consistent 0\(ms\) ignition delay. So though there is a lower pressure, all measurements were subject to the same cyclic pressure waves, and the spark discharge timing was not changed. The pressure does oscillate about the tank pressure, so the pressure was not adjusted. To remove the
expansion wave causing this fluctuation, a different gas injection procedure would be needed, which would involve an entirely different engine design.

As previously stated, using a PCB pressure transducer to find ignition time presents values that are about 10-15% faster than OH imaging. This is a numerical value that could have been integrated into the calculations in Section 4.5, but as presented by (Knick 2006), this sounds like a consistent error that does not vary much between measured data points. It is understood that all values presented in this paper are dependent on this measurement technique, and accepted as the ignition time.

The equivalence ratio uncertainty is found using the elemental errors in measuring fuel flow rates. The oscillating pressure from the open and close of the fill valves will cause addition error in the aviation gasoline equivalence ratio. The pressure buildup behind the valves, when they are closed, creates flow velocity oscillations in the gases. The pressure oscillations have a similar effect on the gaseous fuel flows, thus the gaseous fuel equivalence ratios are not substantially effects by the flow oscillation. However, as the pressure oscillations affect the gaseous flows, the liquid fuel injection is not affected, and continues to flow at a constant rate. This produces an oscillation in the equivalence ratio. (Tucker 2005) examined this effect and found that it produces a maximum equivalence ratio oscillation of ±23%. However, mixing takes place in several locations between the fuel injection point and the fill manifold. Thus, this oscillation is likely overstated and was not added to the error bars of the results.

The DDT process is non-linear and these values were found using a linear assumption. The non-linear effects can not be quantified without knowing the change in wave speed with respect to time. Rather than assuming a trend for the wave
acceleration, we just realize that the DDT location has to be between the two wave speed measurement locations. This yields a 6" span over which the DDT location can lie. This yields 3" to each side of the interval’s center. Since the systematic uncertainty is $\pm 0.105m \ 4.126”$, the smaller error introduced from the linear assumption will be overshadowed by the current and slightly overstated systematic error. Thus, the systematic error was not modified from the linear assumption.
Presented in this chapter is all of the results from the testing and modeling of this research. It begins presentation of C-J wave speeds that were calculated for each fuel, then ignition times, DDT times, and DDT distances are presented for aviation gasoline for multiple ignition systems. Then the same results are laid out for ethylene and lastly hydrogen. Following the presentation of all these plots, is an explanation of discrepancies in a few of the results. Lastly, an overview of the work done is given, with an explanation of future research possibilities stemming from these results.

5.1: The Chapman Jouguet Velocities

The C-J velocities were measured for each fuel at different equivalence ratios and pressures. For hydrogen, the results are presented in Figure 5.1.
Figure 5.1: The C-J speeds of the hydrogen/air mixtures as a function of the equivalence ratio and initial pressure.

The gray line denoted as “Detonation Database” is a plot of the numerical results found by (Kaneshige and Shepherd 1997). The measured C-J speeds are in agreement with the general trend of the detonation database results, and are very close in numerical value. Another important observation is as pressure increases, so does the C-J speed.

The C-J speed of the ethylene/air mixture was also examined for the equivalence ratios tested. The result is presented in Figure 5.2.
Figure 5.2: The C-J speeds of the ethylene/air mixtures as a function of the equivalence ratio and initial pressure.

Again, values are very close to those presented by detonation database, denoted by the gray line. Again, the C-J speed increased with elevated initial pressure. The error bars of the data from two different pressures overlap, but the trend showing increased C-J speed with increased initial pressure still remains.

Next, the C-J speed of the aviation gasoline/air mixture was explored. These values are very important, as there were no available numerical C-J speeds for aviation gasoline. The results of testing are shown in Figure 5.3.
Figure 5.3: The C-J speeds of the aviation gasoline/air mixtures as a function of the equivalence ratio and initial pressure.

The error bars of the aviation gasoline results are larger than those of ethylene and hydrogen. Furthermore, there is no clear trend showing an increase in the C-J speed with increased initial pressure.

Testing of the C-J speeds was done to find wave speeds that were used as criteria for achieving detonation. Multiple pressures were tested. Numerical results from the detonation database show that increased initial pressure would increase the C-J wave speed (Figure 5.4).
The increase in the C-J speed was measured for many conditions of the ethylene/air and hydrogen/air mixtures. Not all results agree with the trend presented in Figure 5.4. Again, results for the aviation gasoline/air mixtures yield no clear trend. The lack of consistency among measured values and the shallow slope of the C-J speed increase with respect to initial pressure, lead to my decision that varying the C-J speed in the calculation of the DDT distance and time would not be fruitful. Instead, the C-J speeds measured with the atmospheric initial pressure were used for all DDT calculations. For consistency, the measured velocities were used since numerical values of the C-J speed for the aviation gasoline/air mixture were not available.
5.2: Aviation Gasoline Results

Of the fuels reported in this thesis, aviation gasoline was the most practical fuel tested. This is due to its high energy density, which is a favorable characteristic for aviation fuels. The results for the aviation gasoline/air mixture showed that the elevated initial pressure considerably shortens the ignition time. Refer to Figure 5.5, where the x-axis variable is the initial pressure.

![Figure 5.5: The ignition time, DDT time, and total detonation time of the aviation gasoline/air stoichiometric mixture as a function of initial pressure. Results are from the MSD ignition system.](image-url)
In Figure 5.5, the line generated by the Chemkin analysis is in good agreement with the ignition time data. The measurement and the Chemkin analysis both show a downward trend with the increasing initial pressure. The Chemkin results are always well within the error bars of the measured ignition time. The DDT time shows a slight increase with pressure, but is more gradual than the decrease of ignition time. Thus, the total time to detonation decreases. This ignition time and DDT time results can be shown over a range of equivalence ratios and pressures (Figure 5.6 & Figure 5.7).

Figure 5.6: The ignition time of the aviation gasoline/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.
Figure 5.7: The DDT time of the aviation gasoline/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.

As previously discussed, another important parameter is the DDT distance. The measured DDT, because as the initial pressure increases, a small decrease in the DDT distance was shown. Refer to Figure 5.8. The C-J wave speed was assumed to be a constant value, but does increase with the elevated initial pressure. Since at higher initial pressures, the true C-J velocity will be higher than the velocity used, the measured DDT distance and time values will be slightly lower than the actual values at higher initial pressures. DDT distances for multiple equivalence ratios and initial pressures is shown in Figure 5.8.
Figure 5.8: The DDT distance of the aviation gasoline/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.

Aside from the MSD ignition system tested, thermal plasma and transient plasma ignition systems were examined for the atmospheric initial pressure. A comparison of the ignition times from all three ignition systems is presented in Figure 5.9. The plot is for atmospheric initial tube pressure.
Figure 5.9: The ignition time of the aviation gasoline/air mixture as a function of the equivalence ratio, for multiple ignition systems. The initial pressure in the tube was atmospheric.

At the atmospheric initial pressure, the transient plasma system provides the shortest ignition times, followed by the thermal plasma system, and lastly the MSD system. Data obtained for each ignition system follows the same trend when the equivalence ratio is varied. As expected, the plasma ignition systems perform better than the MSD stock automotive ignition, at the atmospheric initial pressure.

The pressure traces obtained by employing the thermal plasma ignition system were slightly different, when the atmospheric initial pressure was tested. Figure 5.10

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shows PCB pressure transducer traces taken from firing cycles initiated by the thermal plasma system. Both runs were for the atmospheric initial pressure.

Figure 5.10: PCB pressure traces for the stoichiometric aviation gasoline/air mixture and atmospheric initial pressure. The thermal plasma and MSD ignition system traces are shown.

The jump in signal half way up the plasma PCB trace caused problems with PTFinder. The pressure trace typically did not achieve a slope of $\frac{5V}{s}$, the criterion for ignition, for a long enough time for the average slope of a PTFinder window to reach a $\frac{5V}{s}$
slope. This caused ignition times returned by the analysis program to be after the jump in signal. In this case, the first ion probe detected a combustion wave before the PTFinder ignition time. Because of this paradox, it was concluded the combustion must begin before the signal jump. To alleviate this PTFinder issue, a slope of \( 4.5 \text{V/s} \) was used as criteria for ignition by PTFinder. This yielded consistent results that were determined to be less than 2% shorter than values returned by the \( 5 \text{V/s} \) slope. This discrepancy has been added to the total uncertainty of these four points, and all other plasma analysis was done with the \( 5 \text{V/s} \) slope.

An interesting trend results when the initial pressure is elevated for the thermal plasma system. Figure 5.11 shows the ignition times of the MSD system and the thermal plasma system.
Figure 5.11: The ignition time of the aviation gasoline/air mixture as a function of the initial pressure, for multiple ignition systems. The stoichiometric equivalence ratio was employed.

As pressure increases, the ignition times from the two systems converge to one another and the thermal plasma system shows no benefit over the stock ignition system. This result is counter intuitive, because the plasma ignition system has more than 5 times the energy discharge in the spark, as compared to the MSD ignition system.

The ignition time trends of the thermal plasma system were similar to the MSD system, when the elevated initial pressures were tested. The measured ignition times for the plasma system are presented in Figure 5.12.
Figure 5.12: The ignition time of the aviation gasoline/air mixture as a function of the equivalence ratio and initial pressure. Results are from the thermal plasma ignition system.

The DDT time and distance also have similar trends, but due to large uncertainties, the error bars of the results overlap (Figure 5.13 & Figure 5.14). Because of ion probe issues, which prevented the calculation of critical wave speeds, there are no DDT results for the atmospheric initial pressure testing.
Figure 5.13: The DDT time of the aviation gasoline/air mixture as a function of the equivalence ratio and initial pressure. Results are from the thermal plasma ignition system.
Figure 5.14: The DDT distance of the aviation gasoline/air mixture as a function of the equivalence ratio and initial pressure. Results are from the thermal plasma ignition system.

5.3: Ethylene Results

Ethylene was another fuel tested with favorable results. Shown in Figure 5.5 is the ignition time, DDT time, and total detonation time as a function of initial pressure.
Figure 5.15: The ignition time, DDT time, and total detonation time of the ethylene/air stoichiometric mixture as a function of initial pressure. Results are from the MSD ignition system.

Again, the Chemkin analysis is in good agreement with the measured ignition time, both showing a reduction as initial pressure increases. The DDT time stays fairly constant through the initial pressures tested, therefore, the total detonation time reduces because of the reducing ignition time. The global reaction theory ignition times are presented and show a near perfect fit to the Chemkin ignition times. Again, the change in ignition time with respect to initial pressure is shown to be consistent over the range of equivalence ratios tested. Refer to Figure 5.6.
Figure 5.16: The ignition time of the ethylene/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.

With the ethylene/air mixtures, the DDT time failed to show any significant trend. In general, the values seem to decrease. However, owing to the large uncertainties in measurement and small changes in time, the trends cannot be completely verified. A plot of the DDT times over a range of equivalence ratios and pressures is shown in Figure 5.17.
Figure 5.17: The DDT time of the ethylene/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.

Again, the DDT distance showed encouraging results, with a visible reduction in measurements. The DDT distance for multiple equivalence ratios and pressures is shown in Figure 5.8.
At four different equivalence ratios, the complete error bar ranges for the atmospheric initial pressure do not overlap the complete error bar ranges of the 295kPa initial pressure data. This indicates that the DDT distance at the 295kPa initial pressure is lower than the DDT distance at the atmospheric initial pressure. It is also encouraging to see that no elevated initial pressure DDT distance measurements are above the atmospheric initial pressure DDT distance measurements.

A comparison of the ignition times resulting from three ignition systems is presented in Figure 5.9.
Figure 5.19: The ignition time of the ethylene/air mixture as a function of the equivalence ratio, for multiple ignition systems. The initial pressure in the tube was atmospheric.

Again, all values were taken at the atmospheric initial pressure. Again, the transient plasma system performed the best. The thermal plasma system yielded better results than MSD system for each data point taken except for the equivalence ratio of 1.3. However, the error bars for the ignition time measurements of the three ignition systems overlap, meaning that better performance cannot be definitively stated.
Figure 5.11 shows the ignition times of the MSD system and the thermal plasma system. Again, the atmospheric pressure condition shows a decrease in ignition time, but as initial pressure rises, no advantage is discernable.

Figure 5.20: The ignition time of the ethylene/air mixture as a function of the initial pressure, for multiple ignition systems. The stoichiometric equivalence ratio was employed.

The ethylene/air mixture ignition times for the thermal plasma system followed similar trends to previous tests and are presented in Figure 5.12.
Figure 5.21: The ignition time of the ethylene/air mixture as a function of the equivalence ratio and initial pressure. Results are from the thermal plasma ignition system.

The DDT time showed no trend for the ethylene/air mixture. The data for the atmospheric initial pressure lies between two elevated initial pressures measurements.

Refer to Figure 5.22.
Figure 5.22: The DDT time of the ethylene/air mixture as a function of the equivalence ratio and initial pressure. Results are from the thermal plasma ignition system.

In Figure 5.23, the DDT distances for the ethylene/air mixture showed a similar trend to that of the aviation gasoline tests. However, the error bars for the measurements are large and overlap one another. Though the data is inconclusive, it is still reassuring to see a consistent trend that aligns with a previous result.
5.4: Hydrogen Results

In this section, hydrogen as a fuel is examined. Hydrogen is not a practical fuel for PDE flight, but provides a different range of detonation initiation times. The purpose of these measurements is to confirm the measurement trends reported in previous sections. The presentation of results in this section will be slightly different than in previous sections. Reasons for the change in format will be explained where appropriate. Figure 5.24 shows the ignition time, DDT time, and total detonation time as a function of initial pressure, for the hydrogen/air mixture.
Figure 5.24: The ignition time, DDT time, and total detonation time of the hydrogen/air stoichiometric mixture as a function of initial pressure. Results are from the MSD ignition system.

Though fewer data points are presented, similar trends, as compared to previous sections, can be seen. The ignition times using MSD and thermal plasma systems are both presented in this plot, and once again they converge to a similar path, i.e., showing no obvious improvement from the thermal plasma system. The DDT times remain fairly constant, possibly even drop slightly. The total detonation time drops, as was the trend with the testing of aviation gasoline and ethylene. Fewer data points make the
process of deciphering the trends of data difficult. Thus, the trends listed here were made based on the data presented and knowledge of the previously discussed results.

Figure 5.25: The ignition time of the hydrogen/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system. Shown in Figure 5.25 are the ignition times produced by the MSD ignition system. Again, the plot confirms that the ignition time reduces with increased initial pressure. In particular, if the 200kPa data set is removed, the error bars between the atmospheric initial pressure condition and 275kPa initial pressure condition only overlap each other at the equivalence ratio of 0.9.
The DDT time and distance were once again sporadic with large error bars that overlap one another. Since the hydrogen/air mixture ignites quickly and easily, the DDT distance is only about 30% longer than the distance between ion probes. Thus, the acceleration of the wave between the ion probes becomes substantial and averaging of wave speeds and other assumptions essentially damp out the numerical differences in waves.

Figure 5.26: The DDT time of the hydrogen/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.
Figure 5.27: The DDT distance of the hydrogen/air mixture as a function of the equivalence ratio and initial pressure. Results are from the MSD ignition system.

Figure 5.28 shows a comparison of the ignition times resulting from use of the thermal plasma and MSD system. The ignition times produced using the transient plasma system, at the atmospheric initial pressure, is not available for the hydrogen/air mixture. The thermal plasma system showed a very slight improvement in ignition time, but improvement was minor enough to be within the error bars of the MSD ignition time measurements.
Figure 5.28: The ignition time of the hydrogen/air mixture as a function of the equivalence ratio, for multiple ignition systems. The initial pressure in the tube was atmospheric.

The error bars are relatively large because of the low ignition time of the hydrogen/air mixtures. A 10% improvement in the ignition time produced by the MSD ignition system would be within the error bars. This is a disadvantage of using a quickly igniting fuel, and could be the reason that no large advantage is shown by the thermal plasma system.
Figure 5.29: The ignition time of the hydrogen/air mixture as a function of the equivalence ratio and initial pressure. Results are from the thermal plasma ignition system.

Figure 5.29 shows the ignition time for the thermal plasma ignition system once again follows similar trends to the aviation gasoline and ethylene testing. Ion probe issues prevented determination of the DDT times and distances for the hydrogen/air mixture using the thermal plasma system. Since the hydrogen undergoes DDT in less than half a meter, ion probe times need to be found as close to the head as possible. Unfortunately, during the plasma testing, the first ion probe was not able to detect any of the combustion waves. Thus, the first location where the wave speed was measured, is beyond the onset of detonation.
5.5: Chemkin

As shown in the previous sections, Chemkin was used to model chemical reactions of ethylene/air and aviation gasoline/air mixtures. In Section 3.8 the method used to determine the onset of ignition was illustrated. The method used to model the ignition system with by varying initial temperature and OH species concentration was also explained. As was seen in the results, these methods yielded reasonable ignition times. Table 5.1 reports the initial temperature and OH concentration combinations used to model the MSD ignition system at multiple equivalence ratios.
### Constant Pressure

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Equivalence Ratio</th>
<th>Temperature (K)</th>
<th>OH Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Ethylene</td>
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### Constant Volume

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<td>Ethylene</td>
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<td>1000</td>
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</table>

Table 5.1: The initial temperatures and OH concentrations used to model the MSD ignition system in Chemkin.

The aviation gasoline requires a higher initial temperature in order for the Chemkin ignition times to match the measured ignition times. This may very well be a result of the preheating of the air to vaporize the aviation gasoline. Moreover, a finite-rate mechanism for the combustion of iso-octane was used to model the combustion of the aviation gasoline/air mixture. Thus, there will be some error, since the aviation gasoline is not just iso-octane.
The onset of combustion under both constant-volume and constant-pressure conditions were examined. In reality, the process is likely between the two. Figure 5.30 shows the comparison of results from the constant-pressure simulation to the results from the constant-volume simulation.

Figure 5.30: Chemkin ignition time estimates for the stoichiometric ethylene/air mixture as a function of initial pressure. Constant pressure and constant volume estimates are presented.

The results in Figure 5.30 closely mimic one another. The difference in estimates ignition times is less than ±0.5%. This is reasonable, because major changes in volume and/or pressure do not begin until combustion is fully developed. In subsequent results, the constant-pressure condition is employed. This condition was
chosen since the spark is igniting a deflagration that then transitions to a detonation, and a deflagration can be approximated as a constant pressure process.

One of the major benefits of simulating the onset of ignition with Chemkin is the capability to extrapolate the results to higher pressures numerically. Extending the initial pressures to higher levels can give reasonable estimates for the pressure needed to reduce ignition times to the desired time scales. A plot of the ignition times found by using Chemkin is presented in Figure 5.31. The ignition times continue to reduce as pressure increases, until the auto-ignition pressure is reached, where the ignition time becomes zero.
Figure 5.31: The ignition times calculated by Chemkin for stoichiometric ethylene/air and aviation gasoline/air mixtures as a function of initial pressure.

### 5.6: General Trends and Discrepancies

In previous sections, experimental results were presented for aviation gasoline, ethylene, and hydrogen testing. In general, experimental results for the ignition times of all three fuels followed a similar trend, i.e., higher initial pressures lead to shorter ignition times. Also in previous sections, Chemkin modeling was used to confirm these trends. Global reaction theory ignition time trends, as described by (Lefebvre, et al. 1986), were compared to results from ethylene testing. These trends also gave favorable results that were very similar to the Chemkin ignition times. Experimentally
determined constants used in global reaction theory were not available for aviation gasoline or hydrogen combustion. Thus, only comparison to ethylene combustion was presented.

Previous measurements also show that the DDT times and distances decrease with increased initial pressure (Chapin, et al. 2007). The ethylene and hydrogen measurements show either a constant DDT time or decreasing DDT time, but the aviation gasoline DDT time measurements appear to increase. The DDT distances for all three fuels, while inconclusive at times, does show a general reduction with increasing initial pressure. This shows that the ion probe times yield reasonable results. Thus, the increase in the DDT time is either a unique characteristic of aviation gasoline, or can be attributed to the ignition time measurement method.

As discussed previously (Tucker 2005), the ignition time measurement using PCB pressure transducer traces results in ignition times up to 15% faster than the OH imaging technique. The DDT time calculation involves finding the detonation time and subtracting and then ignition time. Thus, the remaining fraction of the ignition time that is not included in the ignition time measured by the PCB transducer is added to the overall DDT time result. With the longer ignition time of aviation gasoline, this can add enough time to overcome the inherent benefits of the elevated pressure on DDT time. This can have an overall effect on the variation of the DDT time with respect to initial pressure. This is of course assuming that the pressure has a more drastic effect on the ignition time than the DDT time. Ethylene and hydrogen both have the up to 15% of actual ignition time added into their respective DDT times also, but the lower ignition times of these fuels results in a smaller effect on the trend of the DDT time.
The C-J wave speed was assumed to be a constant value, but does increase with the elevated initial pressure. Lower C-J speeds could aid in reducing the DDT distances and times. Lower C-J speeds, will be reached sooner than the higher C-J speed that the elevated initial pressure induces. However, this effect is minimal since the increase in C-J speed with initial pressure is minimal. The change in C-J speed is small enough to be within the total uncertainty displayed.

As previously stated, the thermal plasma system resulted in a decrease in the ignition time at the atmospheric initial pressure. However, when elevated pressures were studied, the ignition times followed a shallower decrease until no appreciable benefit over the MSD ignition results could be seen. To get a possible explanation of this, Chemkin results are examined. Shown in Figure 5.32 are the ignition times calculated by Chemkin for the ethylene/air mixture at various temperatures. The results are a function of the initial pressure and are calculated for the stoichiometric equivalence ratio. The OH species concentration was once again varied by way of the method described in Section 3.8.
As initial temperature increases, the ignition time reduces more gradually with increasing initial pressure. This could explain the ignition times found using the thermal plasma system not dropping as quickly as the MSD ignition system. Figure 5.33 shows the ignition times of the thermal plasma and MSD systems yielding different reducing rates with respect to initial pressure.
Figure 5.33: The measured ignition time of the ethylene/air mixture as a function of the initial pressure, for multiple ignition systems, with a power trend line for each ignition system’s results. The stoichiometric equivalence ratio was employed.

The thermal plasma ignition system is likely characterized by a discharge of a hotter spark with less OH production than the MSD system. This implies that as initial pressures get higher, the MSD ignition system will perform better than the thermal plasma ignition system, which discharges more energy than the MSD system. In this thesis, this preliminary classification of the thermal plasma ignition system was carried out. Further investigation should focus on changing the initial temperature and OH concentration in order to match the measured ignition times.
5.7: Ignition Time Repeatability

Analysis was done to discern if the results found with the above methods were repeatable. While testing to measure C-J speeds, head pressure traces were taken to calculated the ignition times, rather than repeating the entire ignition time study. The pressure traces are used for analysis to see if the same setup and ignition time measurement method can reproduce the ignition times found in previous tests. The ignition times were calculated for the atmospheric initial pressure for each of the fuels. Figure 5.34 shows the ignition times for aviation gasoline/air mixtures, measured at two different times. The physical setup was torn down and reconstructed between measurements, and a 3 month time span passed between the measurement dates.
Figure 5.34: Two data sets of the ignition time for the aviation gasoline/air mixture as a function of the equivalence ratio, to show repeatability. The initial pressure was atmospheric and the MSD ignition system was employed.

In Figure 5.34, two data sets of the same measurements, obtained at different dates are presented. The March measurement lies within the error bars of the initial measurement. The error bars represent the range that has a 95% likelihood of the measured ignition times being within its limits. It can be concluded that the measurement is repeatable because the ignition times measured in March are within the error bars of the similar measurement taken in December. A similar result was found for hydrogen/air and ethylene/air mixture testing.
Figure 5.35: Two data sets of the ignition time for the ethylene/air mixture as a function of the equivalence ratio, to show repeatability. The initial pressure was atmospheric and the MSD ignition system was employed.
Figure 5.36: Two data sets of the ignition time for the hydrogen/air mixture as a function of the equivalence ratio, to show repeatability. The initial pressure was atmospheric and the MSD ignition system was employed.

In Figure 5.35 and Figure 5.36, two data sets of the measured ignition times are plotted for the ethylene/air and hydrogen/air mixtures, respectively. Terming the initial measurement as the primary measurement, and the repeatability measurement as the secondary measurement, levels of repeatability can be stated. For a measurement to be repeatable at all, the error bars from both the primary and secondary measurements need to overlap. A measurement is considered to be more repeatable if the secondary measurement lies inside the error bars of the primary measurement. The results for hydrogen and ethylene show that the measurements are repeatable.
A similar test was carried out with elevated initial pressure. Similar repeatability was found. In many cases the two sets of results have better agreement. The plots for these were not shown for the interest of conciseness of the present thesis. Overall, the repeatability analysis showed that the ignition time data were by in large repeatable for the fuels tested. The repeatability of the measured DDT time and distance was not examined. In the future, an entirely new set of measurements could be conducted to assess the repeatability of these data.

5.8: Conclusions and Future Application

Elevated initial pressures have conclusively shown to reduce the ignition time in the PDE. While using the stock MSD ignition system, raising the initial pressure from 1 atm to 2 atm has shown to provide a medial 40% reduction in the ignition time. While using the MSD system, we also showed a reduction in the DDT distance, while the measured DDT times were inconclusive for reasons discussed in Section 5.6.

The effect of using the thermal and the transient plasma ignition systems was also investigated. At the atmospheric initial pressure, the plasma systems performed well as compared to the MSD ignition system. The transient ignition system showed a medial 35% improvement in the ignition time while testing aviation gasoline, but only a medial 15% improvement for the ignition time while testing ethylene. The ethylene results remained within the error bars of the MSD system. The thermal plasma ignition system showed a medial 25% reduction in the ignition time while testing aviation gasoline, and a medial 10% reduction of the ignition time while testing ethylene, except a slight increase in ignition time at an equivalence ratio of 1.3.
Hydrogen ignition time showed no real benefit from the thermal plasma system, which may have been caused by the short ignition times and system measurement capabilities. When pressure was increased, the performance of the thermal plasma ignition system was undesirable. As the initial pressure increased, thermal plasma ignition times decreased, but gradually enough for the MSD ignition time results to overlap. Thus, the thermal ignition system yielded improvements at the atmospheric initial pressure, but as higher pressures are reached, it showed no improvement over the MSD ignition system. Thermal plasma DDT times were similar to those of the MSD ignition system, as any change in results were within uncertainties. Table 5.2 shows the percentage reduction of the ignition time with respect to the MSD ignition time at the stoichiometric equivalence ratio and atmospheric initial pressure. Results in this table are presented for various initial pressure and ignition system combinations, and encompass all equivalence ratios. Table 5.3 shows the percentage reduction of the DDT distance with respect to the MSD DDT distance at the atmospheric initial pressure.
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ignition System</th>
<th>Initial Pressure (atm)</th>
<th>% Reduction for Ignition Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation Gasoline</td>
<td>MSD</td>
<td>2</td>
<td>45-55</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>3</td>
<td>55-65</td>
</tr>
<tr>
<td></td>
<td>Thermal Plasma</td>
<td>1</td>
<td>20-30</td>
</tr>
<tr>
<td></td>
<td>Thermal Plasma</td>
<td>2</td>
<td>45-60</td>
</tr>
<tr>
<td></td>
<td>Transient Plasma</td>
<td>1</td>
<td>35-45</td>
</tr>
<tr>
<td>Ethylene</td>
<td>MSD</td>
<td>2</td>
<td>35-45</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>3</td>
<td>50-65</td>
</tr>
<tr>
<td></td>
<td>Thermal Plasma</td>
<td>1</td>
<td>0-15</td>
</tr>
<tr>
<td></td>
<td>Thermal Plasma</td>
<td>2</td>
<td>40-55</td>
</tr>
<tr>
<td></td>
<td>Transient Plasma</td>
<td>1</td>
<td>10-25</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>MSD</td>
<td>2</td>
<td>30-45</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>3</td>
<td>45-55</td>
</tr>
<tr>
<td></td>
<td>Thermal Plasma</td>
<td>1</td>
<td>0-15</td>
</tr>
<tr>
<td></td>
<td>Thermal Plasma</td>
<td>2</td>
<td>45-60</td>
</tr>
</tbody>
</table>

Table 5.2: Percentage reduction of the ignition time with respect to the ignition time using the MSD system at the atmospheric initial pressure.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Initial Pressure (atm)</th>
<th>% Reduction for DDT Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation Gasoline</td>
<td>3</td>
<td>20-35</td>
</tr>
<tr>
<td>Ethylene</td>
<td>3</td>
<td>25-40</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>3</td>
<td>15-35</td>
</tr>
</tbody>
</table>

Table 5.3: Percentage reduction of the DDT distance with respect to the DDT distance using the MSD system at the atmospheric initial pressure.

Total detonation times for each fuel showed potential for increasing cycle frequency. A medial 30% reduction in total detonation time was observed for the initial pressure of 2 atm. This would increase cycle frequency, by decreasing the firing cycle time. In order to actually increase cycle time, the air flow systems would also need to be capable of the increased flow rates. Figure 5.37 shows the increase in cycle
frequency that could be achieved for the aviation gasoline/air mixture, as a function of the wave propagation and exhausting time. Ignition delay is included in the wave propagation and exhausting time also.

Figure 5.37: Frequency capability of the PDE as a function of wave propagation and exhausting time, for multiple initial pressures and the stoichiometric equivalence ratio.

Elevating the initial pressure to 3 atmospheres will yield a maximum frequency increase of 70%. The shorter the wave propagation, exhausting, and ignition delay times, the better the effect of initial pressures on cycle frequency. Assumption to construct this chart include same time allotment for each phase of the cycle, capability
for the air flow system to support the flow demands, and stoichiometric equivalence ratio.

Converging nozzles have been tested in an attempt to raise tube pressure. The nozzle reduces the thrust produced by the PDE, which is an undesired result. An ideal situation for taking advantage of the elevated initial pressures would be in a pre-detonator configuration. In a pre-detonator, the accelerated detonation initiation process would result in a faster detonation initiation. Since the pre-detonator does not directly produce thrust, the nozzle used to increase pressure, will not reduce thrust. The spiral can then be removed from the detonation tube, which will also increase thrust (Hoke, et al. 2006).

Elevated pressures have a positive effect on detonation initiation processes as presented in this thesis. The next step would be to find a method to apply this elevated pressure to the detonation tube, without impeding the tubes ability to produce thrust. Nozzles have been examined, and provide some help, but involve drastic change to the end of the detonation tube, which alters thrusting capabilities. For future development, a pressurized pre-detonator arrangement is suggested.
BIBLIOGRAPHY


