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EXPERIMENTAL INVESTIGATION OF PULSE DETONATION WAVE PHENOMENON*

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ABSTRACT

The subject of this paper is the experimental study of detonation wave phenomenon conducted at the University of Texas at Arlington. This study was conducted to gain a basic understanding of the physical mechanisms governing the evolution of detonation waves in order to develop an operational Pulse Detonation Engine.

The study was conducted in a simple cylindrical test chamber where several parameters could be varied. These parameters were the length to diameter ratio, ignition location, ignition energy, initial pressures, types of fuels and turbulence quality. The detonation characteristics examined were the detonation wave velocities and pressures.

It was observed that the turbulent creating devices and high initial pressures were instrumental in achieving Chapman-Jouguet detonation velocities. It was also observed that detonations were achieved in all of the tests, but the velocities of the detonations were considerably lower than the velocities predicted by theory. Based on these results it was concluded that fuel and oxidizer mixing is the most important factor in achieving a Chapman-Jouguet detonation.

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1.0 INTRODUCTION

Pulse Detonation Engines show a great deal of promise for a variety of applications. The most obvious application is for aerospace propulsion systems. An engine of this type would offer several distinct advantages over traditional engines as well as a wider operating range.[1] A closely related use is in rocket propulsion. Again there are several advantages that a Pulse Detonation Engine would have over conventional rocket motors.[2] This technology may also be used to clean slag off of coal furnaces which would save considerable down time for the furnace. Because of the commercial potential of Pulse Detonation Engines, any one of these applications would justify the development of this technology.

As a result of the promising nature of this technology a detailed study of the properties of detonations needed to be conducted in order to develop devices utilizing detonations. By studying detonation properties such as the detonation velocity, pressure ratios, thrust and the length of time required to complete the detonation cycle, valuable data necessary to design a pulse detonation device were obtained.

The preliminary phase of this study was conducted at the University of Texas at Arlington, with the support of Lockheed, Rocketdyne and the State of Texas. The goal of this study was to gain knowledge about detonations in order to develop a Pulse Detonation Engine.

Theory of Operation

In theory a Pulse Detonation Engine would operate by filling a chamber with a fuel and oxidizer combination, detonating the mixture and then refilling the chamber once the exhaust products are expelled. The cycle describing a detonation is the Humphrey cycle which has a higher efficiency than the cycle of traditional propulsion systems, the Brayton cycle. This is where the advantage of the detonation cycle comes into play. By using the detonation most of the machinery of conventional engines is not necessary. See Reference 3 for an introduction to Pulse Detonation Engines.

The detonation of the mixture can be done in one of two ways. The first of these is to directly initiate a detonation in the fluid by providing a great deal of energy to the fluid. The other method is to initiate a deflagration with a lower energy ignition system and then allow or assist the deflagration to transition to a detonation.

Direct initiation is achieved by adding energy to the mixture fast enough and in sufficient quantity to cause the gas to detonate initially. This can be done by using a laser, an explosive, a shock wave or any other ignition system which meets the speed and energy requirements.

Transition occurs through the combustion mechanisms associated with detonations which are as follows. As the combustion flame accelerates in a tube, the heat that is generated by the combustion process is not allowed to dissipate. This leads to an overall increase in the temperature behind the wave front. At a certain point the temperature rise and the pressure increase will be sufficient to create a shock wave. The shock wave in turn accelerates the flame front because of the rise in temperature and pressure across the shock. When the velocity of the detonation stabilizes, a Chapman-Jouguet detonation is established. See Reference 4 for details on transition.

2.0 FACILITY

The facility for this study has been specially constructed so that many of the parameters could be changed. The test chamber is segmented so that the length can be modified and the location of the ignition can be changed. The injection system also allows for several different fuel and oxidizer combinations and the ignition system can be modified to produce different energy levels and axial locations. Finally, turbulence creating devices and centerbodies can be inserted to change the quality of the flow in the chamber.

Test Chamber

This study was conducted in a simple test chamber with a 7.62 cm (3 in) internal diameter. The test chamber is constructed with 7.62 cm (3 in), 15.24 cm (6 in) and 30.48 cm (12 in) long sections allowing the length to diameter ratio to be changed from 1 to 12 where the diameter remains the same.

Another parameter that can be changed is the location of the ignition point. The arc plug is put into the wall of a 7.62 cm (3 in) section. One end of the chamber is covered with a steel endplate while the other end is covered with a Mylar diaphragm, 0.254-0.381 mm (0.01-0.015 in) in thickness. The entire assembly is securely anchored in place by a thrust stand. When the chamber is assembled, sensor locations are axially separated by 7.62 cm (3 in) along the length of the chamber. The ignition location is at one of these 7.62 cm (3 in) locations in place of a sensor. Figure 2.1 illustrates the test chamber sections.

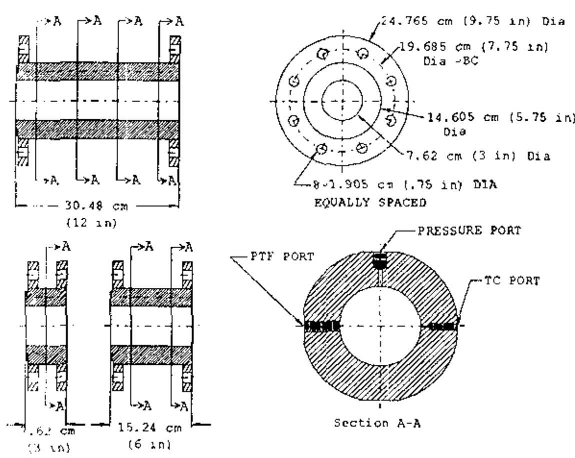

Figure 2.1: Test Chamber Sections

Injection System

The fuel and oxidizer are injected into the closed chamber through the steel plate at the end of the test chamber. Six holes were required to do this. The six lines attached to the endplate lead to the following:

- Fuel - Hydrogen, H2, Methane, CH4, Propane, C3H8.
- Oxygen, O2
- High Pressure Air - Used to dilute the products.
- Vacuum - Evacuates the chamber.
- Vent - Releases the reactants.
- Baratron - Measure the initial pressures.

Figure 2.2 illustrates the injection system.

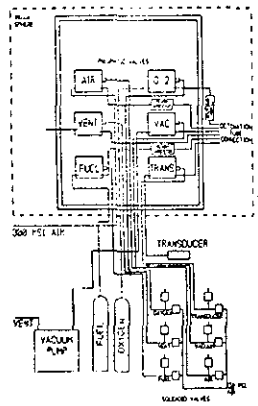

Figure 2.2: Injection System Diagram

Ignition System

Once the fuel and oxidizer are in the test chamber they are ignited using a high energy arc plug. This arc plug is powered by an arc welder and a capacitor bank. The arc welder is used to ionize a path between the two electrodes of the arc plug. When the air path is ionized the capacitors discharge. This discharge creates an arc which provides more energy to the fluid than a spark does because a shock wave is created. A direct initiation of a detonation can be caused in this manner. Details of the ignition system are provided in Reference 5.

Instrumentation

These tests were conducted with instrumentation consisting of PCB Dynamic Pressure Transducers, model number 111a24. This pressure transducer measures the change in pressure from an initial pressure reading for zero volts with a response time of 1 μs and a full-scale range of 6894.8 kPa (1000 psi). Along the length of the test chamber, six transducers may be mounted at 7.62 cm (3 in) intervals. A seventh transducer is mounted in the endplate to provide an estimate of the thrust generated by the detonation.

The other sensor used is the Baratron Pressure Transducer from MKS, model number 127A. This transducer measures the initial pressures in the chamber as was discussed earlier. The maximum pressure that can be safely measured by the Baratron is 1333.22 kPa (10000 Torr). Before the mixture is ignited this transducer is isolated from the test chamber.

The sensors are connected to a DSP Technology Data Acquisition system to record the voltage measurements corresponding to the pressure changes. Each of the 48 channels of the data system has its own independent amplifier and A-D converter with a range of 10 volts. The gain can be set for each of the amplifiers to allow each sensor to use as much of the full range as possible. As the channels are simultaneously sampled, they are stored in the 516K memory buffer in the data system. The data system is set to sample data every 10 μs.

3.0 CONFIGURATION

Since this is a parametric study, a basic configuration needed to be defined so that meaningful comparisons could be made. The base configuration is defined by the length to diameter ratio, ignition location, arc voltage, fuel and oxidizer combination, initial pressure and the presence or absence of turbulent or boundary layer creating devices. The parameters to be varied are based on the defining properties for the base configuration.

Base Configuration

The base configuration consists of three test sections. The ignition section is located next to the endplate and the 15.24 cm (6 in) section is connected to it followed by the 30.48 cm (12 in) section. This gives a length to diameter ratio of 7. The capacitor bank consists of two capacitors. Hydrogen and Oxygen are the fuel and oxidizer, respectively, and are ignited at an initial pressure of 1 atm. Finally, the turbulator and the centerbody are not included in this base configuration.

Parametric Variations

The base configuration has a length to diameter ratio of 7. This is varied to 5 and 3 by removing the 15.24 cm (6 in) and 30.48 cm (12 in) test sections, respectively. The next variation is to move the ignition location from the closed end to the open end at 15.24 cm (6 in) intervals. Varying the ignition energy is the third parameter to be varied. This is done by adding two capacitors or by removing a capacitor from the base configuration. The initial pressure is the next parameter to be varied for the three fuels. This yields ten combinations, hydrogen, methane and propane at 0.5, 1, and 2 atm and methane at 3 atm. Finally, a turbulence generator (coiled wire with 3.81cm (1.5 inch) spacing between coils), and a 2.54 cm (1 in) diameter centerbody are inserted into the base configuration at different times.

4.0 DATA ANALYSIS

The data from the pressure transducers is saved in a file in machine language form. Using FORTRAN computer codes these files were broken down into their respective channels and converted into integers in ASCII format. These values were converted into pressure readings using the correlation curves for the pressure transducers and using the Baratron pressure as the initial pressure. Once this was done, pressure plots were made of each of the runs that were studied. From these plots the time of flight velocities were calculated using linear interpolation between common points on each of the pressure spikes. This was compared to velocities calculated using the pressure ratios for each pressure spike through the Mach wave relations.

$$V = \sqrt{\frac{\gamma + 1}{2\gamma}\left[\frac{P_s}{P_i} - 1\right] + 1} \cdot a_i$$

where P_s = Shock Pressure
P_i = Initial Pressure
γ = Specific Heat Ratio
a_i = Speed of Sound

Finally, both of these velocities were compared to the theoretical Chapman-Jouguet detonation velocities calculated for stoichiometric mixtures using the Thermal Equilibrium Program, TEP™, developed by NASA.[6]

5.0 RESULTS AND DISCUSSION

The final results will be summarized in the form of velocity plots or wave diagrams, directly comparing the base configuration with the variable configurations. Each configuration will have both the time of flight calculated velocities, (represented by solid symbols on the plots) and the pressure ratio calculated velocities, (represented by outlined symbols on the plots) the Chapman-Jouguet velocities, and the sonic velocity in the unburned portion of the gas.

Base Configuration

An example of the pressure plots is illustrated in Figure 5.1 for the base configuration.

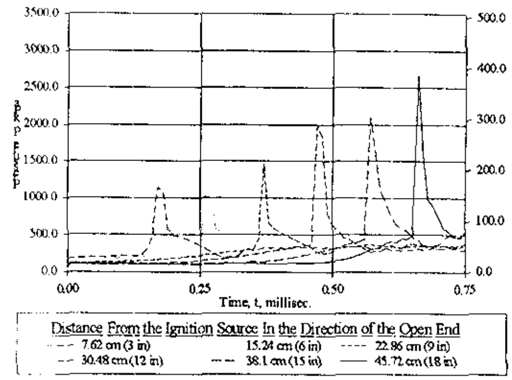

Figure 5.1: Pressure Plots of the Base Configuration

The time axis does not start at the ignition time but at an arbitrary time later in the cycle in order to increase the resolution of the plot. As can be seen, the pressure spikes increase as the shock wave travels down the test chamber. This is the result of a pre-compression phenomenon which increases the initial pressure just prior to the shock wave.

As the shock wave of the detonation passes through the fuel/oxygen mixture a boundary layer is formed along the surface of the chamber following the shock wave. In this boundary layer the flame accelerates pushing the shock wave further ahead of the flame near the wall. This increases the pressure ahead of the main shock wave. When the initial pressure is increased the shock pressure increases. However, the overall pressure ratio for the shock wave does not vary significantly as is shown in Figure 5.2.

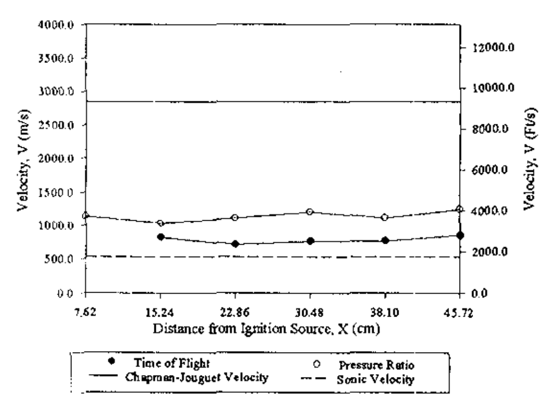

Figure 5.2: Velocity Plot for the Base Configuration

The pressure ratio calculated velocity is higher than the time of flight velocity, but both velocities are above the sonic velocity meaning that a detonation has occurred. The difference between the two velocities is caused by the acceleration error of the pressure transducers.

Since a stable detonation was observed, direct initiation of a detonation did occur. This result will be discussed in detail in an upcoming paper by Taylor and Wilson, Reference 5.

The velocity of the detonation is lower than that predicted by the TEP Code. Poor mixing causes the fuel and oxygen to remain separated and thus leaves pockets of unmixed gases in the chamber. The well mixed areas are detonated, and themselves detonate other pockets. This chain reaction is enough to establish a detonation, but since some of the fuel and oxygen are not detonated, it lacks the strength of a Chapman-Jouguet Detonation because the unreacting gases act as baffles for the detonation wave. This problem is evident in all of the test runs.

Different Fuels and Initial Pressures

The first variation to be conducted was on the type of fuel used for the tests. The first fuel used was Hydrogen. As can be seen in Figure 5.3 the variation of the initial pressure did affect the velocities of the detonations dramatically.

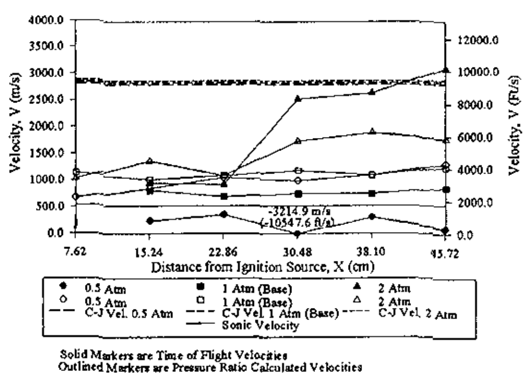

Figure 5.3: Velocity Plot for Hydrogen at Initial Pressures of 0.5, 1 and 2 Atm

The first trend to note is the difference between the velocity plots for the 0.5 atm test. This is due to the difficulty in determining the location of the pressure wave as is passes the pressure transducers. Detonation at this pressure is characterized by a very unsteady process. When the detonation begins to travel down the chamber it dies out to a deflagration, but the deflagration continues. Eventually, a detonation reestablishes in the chamber. This occurs between sensor stations five and six. As a result the negative velocity is not valid on the time of flight measurement plot.

The next trend to be noticed is that the velocity of the wave increases as the initial pressure is increased. In fact the time of flight velocity for the 2 atm test indicates that a Chapman-Jouguet Detonation was achieved. However, the pressure ratio calculations indicate that the velocity increased only slightly. This difference is due to the data acquisition system having too low a resolution to catch the von Neumann pressure spike.[3] Therefore, the velocity is lower for this type of calculation.

The next fuel tested was Propane. Velocity plots for the Propane tests are in Figure 5.4.

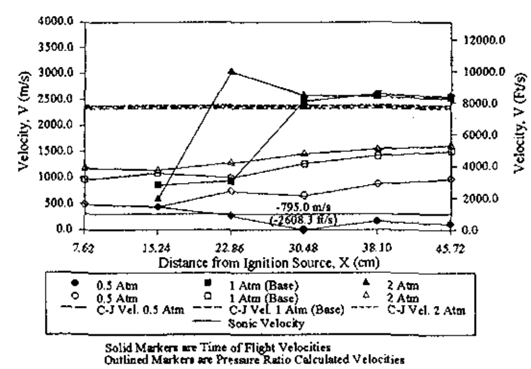

Figure 5.4: Velocity Plot for Propane at Initial Pressures of 0.5, 1 and 2 Atm

Once again, the dieing out and re-establishment of the detonation is seen in the 0.5 atm test. Also, the same trend of increasing velocity as the initial pressure was increased can be observed in this test. The difference between Propane and Hydrogen as fuels is that Propane detonations achieve Chapman-Jouguet detonations at both 1 atm and at 2 atm, instead of at just 2 atm.

The last fuel to be used was Methane and Figure 5.5 contains the velocity plots for these runs.

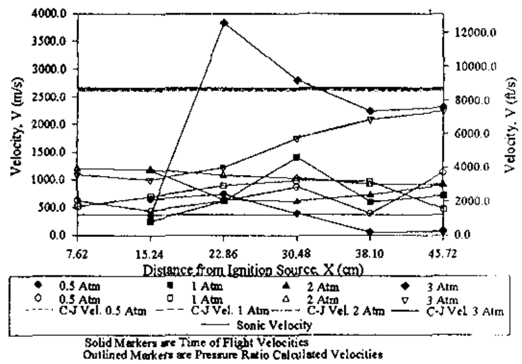

Figure 5.5: Velocity Plot for Methane at Initial Pressures of 0.5, 1, 2 and 3 Atm

The methane test is virtually identical to the to the Hydrogen run with the single exception that the initial pressure had to be increased to 3 atm in order to obtain a Chapman-Jouguet Detonation for methane and that the wave was difficult to track at one atmosphere. In the 0.5 atm test the detonation never reestablishes itself, and therefore; it never comes back up above the sonic velocity once it died out.

Length to Diameter Ratio Variation

The next parameter to be varied was the length to diameter ratio holding the diameter constant. The velocity plot for these test is shown in Figure 5.6.

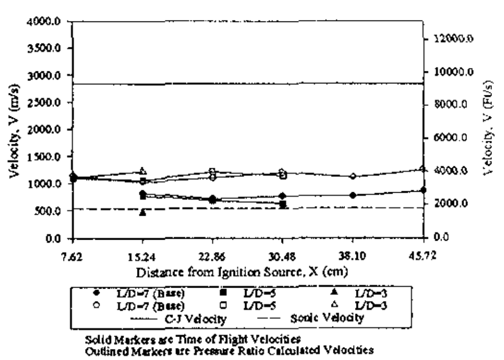

Figure 5.6: Velocity Plot for Length to Diameter Variation

The variation between the velocity plots is very small meaning that the length of the chamber does not significantly affect the velocity of a detonation. The small effect that is noticed is due to the establishment process of the detonation. Establishment of a planar detonation wave appears to take between 7.62 cm and 15.24 cm (3-6 in). As the length of the chamber decreases, this establishment becomes a larger part of the total length of the chamber. For the length to diameter ratio of 3 this dominates and produces a very low velocity.

Ignition Location

The effect due to variation of ignition location is illustrated using the wave diagram in Figure 5.7.

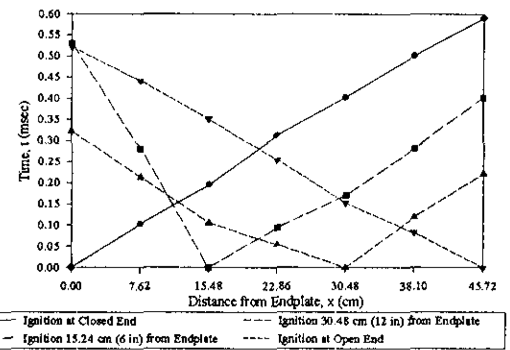

Figure 5.7: Wave Diagram for Ignition Variation with H_2-O_2

The trend to notice here is that the ignition location does not significantly affect the velocity of the detonation when it is located at either end of the chamber. However, when it is in either of the two intermediate locations the velocity of the detonation traveling the shorter distance is lower than the other detonation. The longer distance produces a larger expansion volume than the smaller volume which creates net movement of the fluid toward the larger volume. Thus, the shorter distance has a lower velocity.

Energy Variation

The ignition energy variation is shown below in Figure 5.8 and had no effect on the velocity of the detonation wave. However, it is important to note that in each case the detonation was directly initiated.

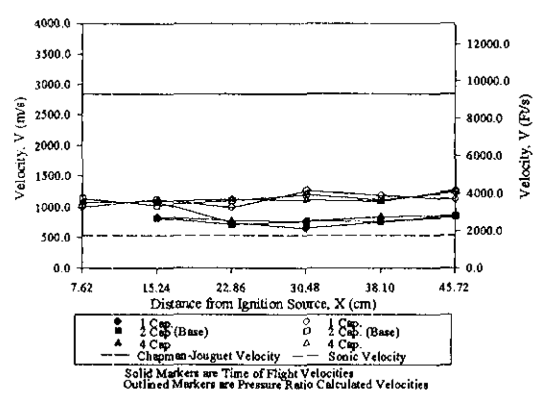

Figure 5.8: Velocity Plot for Ignition Energy Variation

Inserts

Two inserts were placed in the test chamber, a coiled wire to create turbulence and a centerbody to increase the boundary layer volume. In Figure 5.9, the velocity plots of these last two tests are plotted.

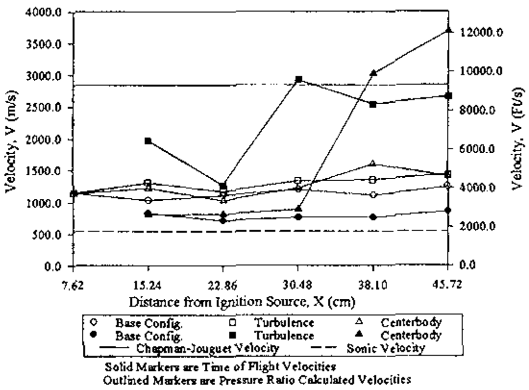

Figure 5.9: Velocity Plot for the Inserts

This plot shows very interesting results. The turbulence creating device increases the time of flight velocities but does not seem to affect the pressure ratio velocity. The centerbody had similar results with the exception that the centerbody was accompanied by a slight rise in the pressure ratio velocities. Because the turbulence and increased boundary layer both accelerate the flame velocity of combustions, a Chapman-Jouguet Detonation is apparent. The relative steadiness of the pressure ratio velocities, however, indicates that the detonation does not increase in strength but simply accelerates for the turbulence creating device and accelerates while gaining only marginal strength for the centerbody.

6.0 UNCERTAINTIES

Due to the nature of the test setup, several unforeseen uncertainties in the results were found. When the test chamber is evacuated a small amount of air can not be removed from the chamber. Also, since the fuel and oxygen are injected into the chamber through the endplate at different times the mixing of the fuel and oxygen is not very thorough. The slower detonation velocities are a result of this mixing problem.

The second set of uncertainties is related to the pressure transducers. The first problem with the sensors is that they are very sensitive to accelerations. When the sensors experience an acceleration, an error of 68.9 Pa/g (0.002 psi/g) occurs. This accounts for the higher velocities calculated from the pressure ratios. Next, the data acquisition system is not capable of sampling data fast enough to observe von Neumann Pressure Peak.[4]

Finally, the last difficulty in this experiment is the diaphragm. Having a diaphragm on one end of the chamber causes a reflected shock to rebound off of it when it is broken. This seriously complicates the analysis of the length of the cycle and the analysis of the pressure after the shock.

7.0 CONCLUSION AND RECOMMENDATIONS

Based on these results several conclusions can be made concerning detonations. The first is that mixing is very important to the detonation process. If the reactants are not thoroughly mixed then the detonation does not develop into a Chapman-Jouguet detonation. It does detonate but only in small, localized pockets. These local detonations send out shock waves which detonate other small pockets. In this manner the detonation waves reach a steady state velocity well below the Chapman-Jouguet velocity which is obvious from the results.

This conclusion is further supported by the turbulent test and the centerbody test where the fuel and oxygen are mixed due to the increased mixing mechanisms of turbulence and increased boundary layer volume. The next support of this phenomenon is the fact that at increased pressures the pockets of unmixed gases are smaller which brings the reactants closer together allowing a Chapman-Jouguet detonation to develop. Finally, since the propane molecules are closest in size to the oxygen molecules, they mix the best. This is evident in that propane is the only fuel that detonated with no aids at one atmosphere. The hydrogen was easier to detonate than the methane because of its higher energy content.

Possibly the most important conclusion is that the ignition system provided more than enough energy to directly initiate a detonation. Since this ignition system can be run at higher frequencies it appears to be an excellent method of avoiding the transition problem and may be effective for fuel/air mixtures as well. As indicated earlier the ignition system will be discussed in detail by Taylor and Wilson. Reference 5.

Another conclusion that can be drawn from these experiments is that the physical geometry is not important to the detonation process. This allows any geometry to be used that is convenient. For a pulse detonation device this is significant in that the length can be set for whatever frequency is desired, and the ignition location can be put anywhere along the chamber to maximize the thrust. This will be discussed in a forthcoming paper by Stanley, Stuessy, and Wilson, Reference 7.

From this investigation, it is obvious that more study needs to be devoted to the mixing problem. Methods for increasing the mixing rate such as turbulence creating devices and added boundary layer volume need further study, with special emphasis on how these methods affect the cycle rate and the propulsive ability of a chamber employing these devices. Finally, the ignition system should be examined in great detail in order to make it a useful aspect of Pulse Detonation Engines.

ACKNOWLEDGMENT

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REFERENCES

1. Nicholls, J. A., Wilkinson, H. R., Morrison, R. B., "Intermittent Detonation as a Thrust-Producing Mechanism," *Jet Propulsion*, May 1957, pp. 534-541.

2. Kim, K., Varsi, G, and Back, L. H., "Blast Wave Analysis for Detonation Propulsion," *AIAA Journal*, Vol. 15, No. 10, 1977, pp. 1500-1502.

3. Bussing, T. R. A., Pappas, G., "An Introduction to Pulse Detonation Engines," AIAA Paper 94-0263, Jan., 1994.

4. Zaturska, M. B., "An Elementary Theory for the Prediction of Critical Conditions for Thermal Explosion," *Combustion and Flame*, Vol. 32, 1978, pp. 277-284.

5. Taylor, D., and Wilson, D. R., "Pulsed Detonation Engine Ignition System Design," AIAA Paper 95-2526, 1995.

6. Gordon, S. and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouget Detonations," NASA SP 273, 1971.

7. Stanley, S. B., Stuessy, W. S., Wilson, D. R., "Experimental Investigation of Pulse Detonation Wave Phenomenon as Related to Propulsion Application," AIAA Paper 95-2580, 1995.