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Experimental Investigation of Pulse Detonation Wave Phenomenon as Related to Propulsion Application

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EXPERIMENTAL INVESTIGATION OF PULSE DETONATION WAVE PHENOMENON AS RELATED TO PROPULSION APPLICATION*

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ABSTRACT

The subject of this paper is the experimental study of detonation wave phenomenon as related to propulsion applications. This study was conducted at the University of Texas at Arlington to aid in the development of Pulse Detonation Engines.

A simple sealed-off cylindrical test chamber was used to determine the effect of various parameters including the length to diameter ratio, ignition location, initial pressure, and different fuels on thrust production. Turbulence creating devices were also used in the chamber to produce turbulent mixing. Finally, a stratified test was conducted to determine the viability of a pre-ignitor concept where a fuel and oxygen mixture was used to detonate a fuel/air mixture.

It was concluded that detonations required a length of time to establish a planar steady state in the chamber. Also, mixing of the fuel and oxidizer was found to be very important. Turbulence creating devices which aided in the mixing of the fuel and oxidizer decreased the amount of thrust produced but did accelerate the detonation to a Chapman-Jouguet velocity. The thrust was strongly influenced by whether the detonation was a Chapman-Jouguet or a low velocity detonation. From the stratified experiments, the pre-ignitor concept showed a great deal of promise.

1.0 INTRODUCTION

Conventional engines are nearing a point where they cannot be improved much further. Already the efficiencies of current engines are limited by the thermal efficiency of the Brayton cycle, which in turn is limited by the maximum temperatures that engine materials can withstand.[1] As a result there are two options open to the propulsion industry for increasing efficiency in propulsion systems. The first is to develop new high temperature materials so that the Brayton cycle efficiency can be increased. The second is to develop propulsion systems where the temperature limitation of the material is not an issue.

One example of an alternative propulsion system is nuclear propulsion.[2] Obviously, this propulsion system has the drawback of producing radioactive material and poses great challenges to public safety. Another alternative is electric propulsion. Unfortunately, this type of propulsion is generally not powerful enough to meet today's propulsion requirements.[2] There are other propulsion alternatives, but for the most part they are impractical or pose very serious challenges. However, one concept that appears very feasible and is currently being developed by several different organizations is the Pulse Detonation Engine. This concept is based on detonation or supersonic combustion instead of deflagration or subsonic combustion which conventional engines use.

Detonation engines fall into two categories: Pulse Detonation Engines and Oblique Detonation Wave Engines. The latter engine is a prospective hypersonic propulsion system and falls outside the scope of this paper.

Pulse Detonation Engines show a great deal of promise for a variety of applications. The most obvious application is for air breathing propulsion

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systems. An engine of this type would offer several distinct advantages, such as higher efficiencies, specific thrusts, thrust to weight ratios, and simpler designs, over traditional engines as well as offering a wider range of operation.[3] A closely related use is in rocket propulsion. Again there are several advantages that a Pulse Detonation Engine would have over conventional rocket engines including higher efficiency and specific thrust.[4] References 3 and 4 elaborate on these advantages in greater detail.

This study addresses how several parameters affect the thrust production of Pulse Detonation Engines. The varied parameters include length to diameter ratio, fuels used, ignition location, and the presence of turbulence creating devices. Additional information about this study can be found in references 5 and 6.

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 Pulse Detonation Engine is based upon the Humphrey cycle which is characterized by constant volume combustion unlike the constant pressure combustion of the Brayton cycle used by conventional jet engines. The Humphrey cycle is more efficient than the Brayton cycle and does not require any turbomachinery, thus making Pulse Detonation Engines simpler in design than current engines. See Reference 7 for an introduction to Pulse Detonation Engines.

The challenges of this engine lie in the areas of the injection and ignition systems which together determine whether or not a Chapman-Jouguet detonation is obtained. The injection system is required to input a considerable amount of fuel and oxidizer in the correct proportions into the chamber at high frequency. Once the fuel and oxidizer are in the chamber an ignition system capable of discharging sufficient energy at high frequency is required to achieve a detonation. Finally, after the fuel and oxidizer are detonated, a stable, planar Chapman-Jouguet detonation wave must be established in a very short distance. All three challenges must be overcome before this engine can become a reality, and this program attempts to address all of these issues with this paper focusing primarily on the issue of Chapman-Jouguet detonation development.

2.0 FACILITY

This study was conducted in a simple test chamber with a 7.62 cm (3 in) internal diameter and a circular cross-section. The test chamber was 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. Based on the cell size of the detonations for the three fuels that were studied, it was concluded that a 7.62 cm (3 in) diameter would be large enough to allow each fuel to detonate.

One end of the chamber was covered with a steel endplate while the other end was covered with a Mylar diaphragm, 0.254-0.381 mm (0.01-0.015 in) in thickness. The entire assembly was securely anchored in place by a thrust stand. When the chamber was assembled, pressure transducer ports were spaced at 7.62 cm (3 in) intervals along the length of the chamber. One pressure port was also placed in the endplate. Figure 2.1 is an illustration of the test chamber setup.

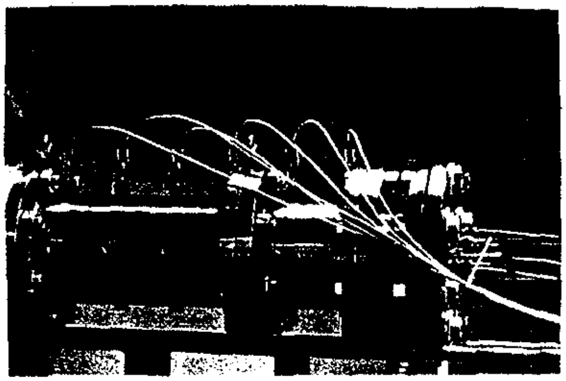

Figure 2.1: Test Chamber Setup

After the chamber is vacuumed down the fuel and oxidizer are injected into the closed chamber through the steel endplate separately, and with no pre or post mixing. The three fuels used in this study were hydrogen, H_2, methane, CH_4, and propane, C_3H_8 in combination with oxygen, O_2. See Reference 6 for a more detailed description of the test facility.

Once the fuel and oxidizer were in the test chamber they were ignited using a high energy arc plug. The high energy arc plug was designed to create an arc discharge across two electrodes after the air path between them was ionized. A direct initiation of a detonation could be achieved in this manner. The arc plug was mounted in the wall of the chamber in a 7.62 cm (3 in) section.

These tests were conducted with instrumentation consisting of PCB Dynamic Pressure Transducers, model number 111a24, with a range of 6894.8 kPa (1000 psi) and a response time of 1 μs. The initial pressure was measured using a 1333.22 kPa (10000 Torr) MKS Baratron Pressure Transducer model 127A. All instrumentation was connected to a DSP Technology Data Acquisition System which has independent 10 Volt amplifiers and A-D converters for each of its 48 channels. The data system is capable of sampling once on each channel every 10 μs. A faster data acquisition system by Le Croy, model 1434A, able to sample 8 channels every 1 μsec was also used as a comparison between the two data systems.

3.0 CONFIGURATION

This study was performed in order to determine the effects of several parameters on the feasibility of Pulse Detonation Engines. The parameters studied were the length to diameter ratio, ignition location, different fuels, initial pressure, and quality of flow in the chamber. Also, a stratified case was studied, where a fuel and oxygen mixture was used to detonate a fuel and air mixture.

Base Configuration

The base configuration consisted of three test sections. The ignition section was located next to the endplate and the 15.24 cm (6 in) section was connected to it, followed by the 30.48 cm (12 in) section. This gave a length to diameter ratio of 7. Hydrogen and oxygen were the fuel and oxidizer, respectively, and were ignited at an initial pressure of 1 atm. The base configuration did not include the use of turbulent creating devices.

Parametric Variations

The initial pressure was the first parameter to be varied for the three fuels. Ten combinations, hydrogen, methane and propane at 0.5, 1, and 2 atm and methane at 3 atm were tested. The length to diameter ratio was then varied from the base value of 7 to 5 and 3 by removing the 15.24 cm (6 in) and 30.48 cm (12 in) test sections, respectively. The ignition location was then varied from the closed end to the open end at 15.24 cm (6 in) intervals. The arc plug was also placed in the endplate.

Turbulence generators were inserted into the chamber next. The first one was a coiled wire with 3.81 cm (1.5 in) spacing between the coils extending 45.72 cm (18 in) down the length of the chamber. This was cut down to 30.48 cm (12 in) long for the next test. Next a wire ring was inserted in the chamber at 15.24 cm (6 in), 30.48 cm (12 in) and then at both 15.24 cm (6 in) and 30.48 cm (12 in) from the ignition location to simulate turbulent points. Finally this was repeated with metal rings with an inner diameter of 6.03 cm (2.375 in).

The last variation was a stratified test where the ignition section was filled with fuel and oxygen, 53.34 cm (21 in) in length, and the downstream section, 30.48 cm (12 in) long, was filled with fuel and air. The fuel and oxygen section was separated from the fuel and air section by a Mylar diaphragm.

Additional tests were performed on the base configuration with the sensors placed on opposite sides of the chamber to determine the characteristics of the detonation as it develops in the chamber. Tests were also conducted with a faster data acquisition system to determine the accuracy of earlier results.

4.0 DATA ANALYSIS

The data from the pressure transducers was 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 for the theoretical Chapman-Jouguet detonation velocities calculated for stoichiometric mixtures using the Thermal Equilibrium Program, TEP™, developed by NASA.[8] Also, comparing the pressure ratios for each pressure spike through the Mach wave relations can be done using the following formula.[7]

$$\frac{P_s}{P_i} = (M_i^2 - 1)\frac{2g}{g+1} + 1$$

where P_s = Shock Pressure
P_i = Initial Pressure
γ = Specific Heat Ratio
M_i= Shock Mach Number

Finally, the instantaneous thrust of the engine was approximated by multiplying the pressure on the endplate transducer by the area of the endplate.

5.0 RESULTS AND DISCUSSION

The final results will be summarized in the form of velocity plots or wave diagrams, and thrust plots. Each configuration had the time of flight calculated velocity, the Chapman-Jouguet velocity, and the sonic velocity in the unburned portion of the gas. The thrust plots of the parametric variations will be compared to the base configuration thrust.

Base Configuration

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

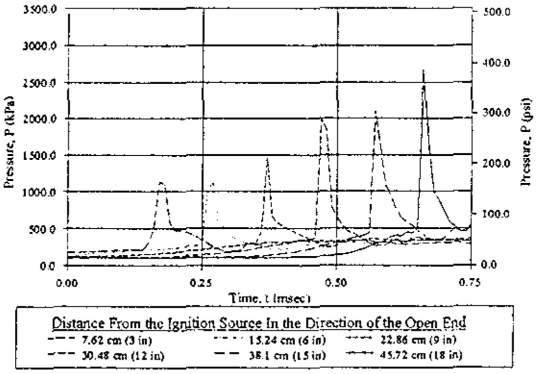

Figure 5.1: Pressure Plots of the Base Configuration with H_2-O_2

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. The ignition delay in this case is lengthy since the first sensor is 7.62 cm (3 in) from the ignition source. Also, the time that the detonation wave takes to reach a planar state is quite long. Unfortunately, a detailed study of this issue could not be done due to material constraints and sensor limitations.

As can be seen, the pressure spikes increase as the detonation 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 induction layer the flame accelerates pushing the shock wave further ahead of the flame near the wall.[9] This increases the pressure ahead of the main shock wave. When the initial pressure is increased the shock pressure increases. Figure 5.2 illustrates the velocity plot for the base configuration.

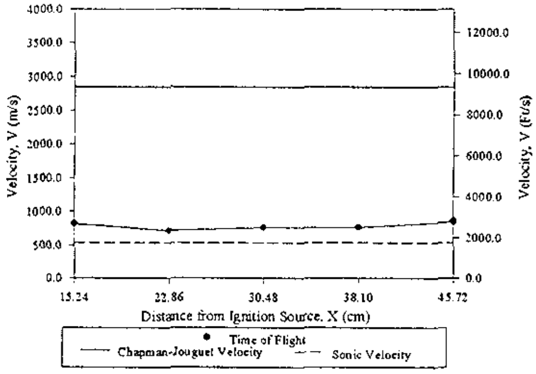

Figure 5.2: Velocity Plot for the Base Configuration with H_2-O_2

These low velocities imply that this is not a Chapman-Jouguet detonation, however; since the pressure ratios are constant across the shock waves, a steady state detonation is evident. If this had been a deflagration preceded by a shock wave then the shock wave would have died out because a deflagration cannot sustain a shock wave.[10]

It is believed that since the fuel and oxygen are injected into the evacuated chamber at separate times with no mixing mechanisms, a poor quality of mixing between the fuel and oxygen occurs. This 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 wave, but since some of the fuel and oxygen does not react, it lacks the strength of a Chapman-Jouguet detonation. This problem is evident in all of the test runs.

The pressure ratios of the detonation can be compared to both the classical Mach wave relations as described in Section 4 and to the TEP™ calculated pressure ratios. This was done for a detonation where a Chapman-Jouguet detonation was achieved in propane and oxygen and is shown in Figure 5.3.

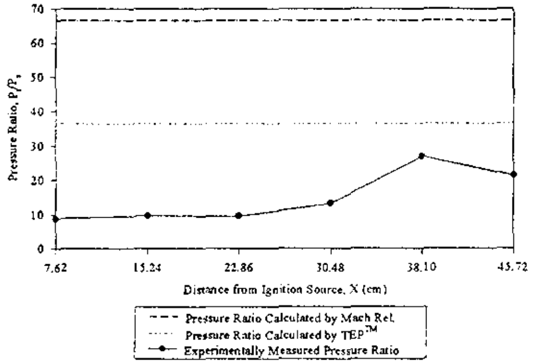

Figure 5.3: Comparison of Pressure Ratios with C_3H_8-O_2

As shown, there is a significant difference between the pressure ratios. Near the ignition the detonation is not a Chapman-Jouguet detonation and thus has a lower pressure ratio. At the end of the chamber, however, the detonation transitions to a Chapman-Jouguet detonation and the pressure ratios increase. The experimental pressure ratios approach the pressure ratios calculated by the TEP™ program but are well below the pressure ratios predicted by the Mach wave relations. This indicates that the Mach wave relation should not be used to approximate the pressure rise across the shock wave of a detonation.

Finally, the thrust plot for the base configuration is shown in Figure 5.4.

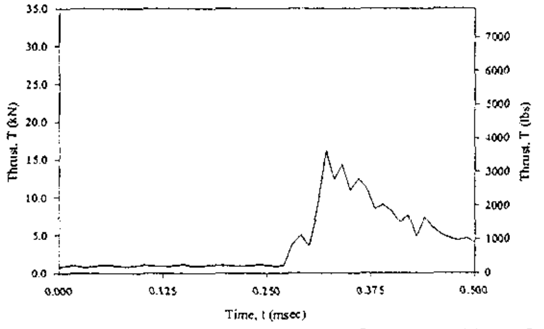

Figure 5.4: Thrust Plot for the Base Configuration with H_2-O_2

As seen, the thrust from a detonation produces a sudden rise followed by a gradual tapering off. This is due to the shock wave suddenly increasing the pressure and then the gases expanding out of the chamber slowly tapering off the thrust. The first smaller pressure rise is believed to be the detonation wave traveling from the ignition hitting the endplate. This occurs before the detonation wave has a chance to coalesce into a planar detonation front, represented by the higher peak.

Different Fuels and Initial Pressures

The first variation to be conducted was the type of fuel used for the tests. The first fuel used was hydrogen. As shown in Figure 5.5 the variation of the initial pressure did affect the velocities of the detonations.

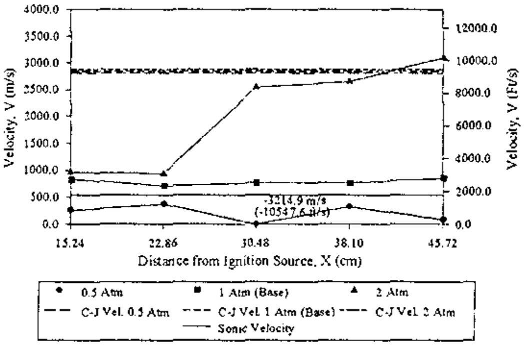

Figure 5.5: Velocity Plot for Hydrogen at Initial Pressures of 0.5, 1 and 2 Atm

At low pressure, the detonation dies out to a deflagration and re-establishes several times down the length of the chamber or the detonation is very irregular in shape and movement. Higher pressures have the inverse effect, namely a Chapman-Jouguet detonation was established following a transition from a low velocity detonation in the 2 atm test.

Figure 5.6 is the thrust plot for the hydrogen initial pressure variation tests.

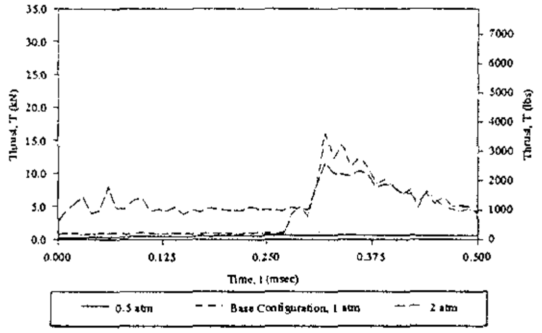

Figure 5.6: Thrust Plots for Hydrogen at 0.5, 1, 2 atm Initial Pressures

As indicated the thrust of the 0.5 atm test is orders of magnitude lower than the base configuration. This is a result of the combustion process oscillating between a detonation and a deflagration. The thrust from the 2 atm or Chapman-Jouguet velocity detonation is also lower than the thrust for the base configuration. In the base configuration, the pre-compression phenomenon raises the shock pressure above that of a Chapman-Jouguet pressure. As an example, a Mach 2 shock wave will have a higher shock pressure than a Mach 4 shock wave if the initial pressure before the Mach 2 shock wave is increased enough. Another possibility for the higher thrust is that in a Chapman-Jouguet detonation the pressure increase is more localized around the detonation wave whereas the pressure in the low velocity detonation, builds up due to the slow wave speed.

The next fuel tested was propane. Velocity plots for the propane tests are in Figure 5.7.

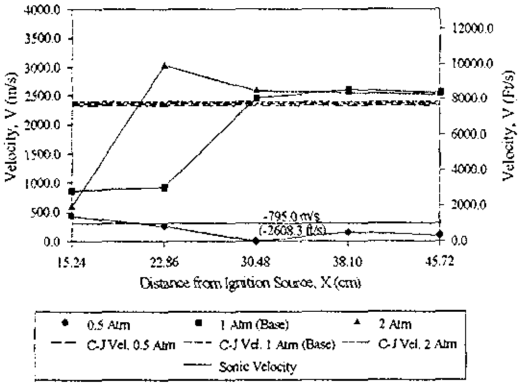

Figure 5.7: Velocity Plot for Propane at Initial Pressures of 0.5, 1 and 2 Atm

Once again, the diminishing and re-establishment of the detonation was seen in the 0.5 atm test. Also, the same trend of increasing velocity as the initial pressure was increased was observed in this test. The propane runs were found to produce Chapman-Jouguet detonations more frequently and sooner than the hydrogen runs. The propane tests achieved Chapman-Jouguet detonations at both 1 and 2 atm.

As Figure 5.8 shows, the Chapman-Jouguet detonation has similar effects on the thrust evolution. The difference from hydrogen was that the thrust from propane is very unsteady but does peak higher than hydrogen. In the 0.5 atm test the pressure does not decrease after the initial pressure rise because the diaphragm did not rupture.

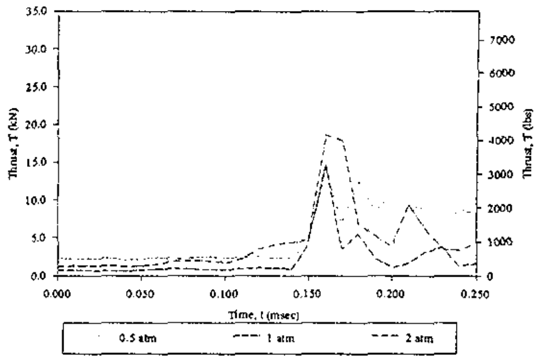

Figure 5.8: Thrust Plots for Propane at 0.5, 1 and 2 atm Initial Pressures

The last fuel to be used was methane and Figure 5.9 contains the velocity plots for these runs.

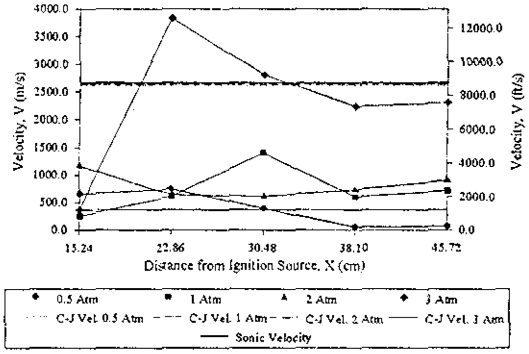

Figure 5.9: Velocity Plot for Methane at Initial Pressures of 0.5, 1, 2 and 3 Atm

The methane tests were virtually identical to the hydrogen tests with the exception that the initial pressure had to be increased to 3 atm in order to obtain a Chapman-Jouguet detonation. In the 0.5 atm test the detonation never re-establishes itself, and therefore, traveled at the deflagration velocity near the end of the chamber.

Figure 5.10 shows the thrust plots for the methane test.

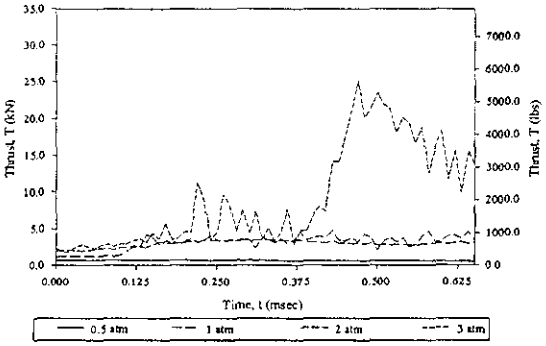

Figure 5.10: Thrust Plots for Methane at 0.5, 1 and 2 atm Initial Pressures

Again the similarities between this plot and the hydrogen plot are apparent. The difference with the methane tests is that the 3 atm test was the only Chapman-Jouguet detonation. Here it is interesting to observe that the Chapman-Jouguet detonation produced much higher thrust levels.

Length to Diameter Ratio Variation

The next parameter varied was the length to diameter ratio. The velocity plot for these tests is shown in Figure 5.11.

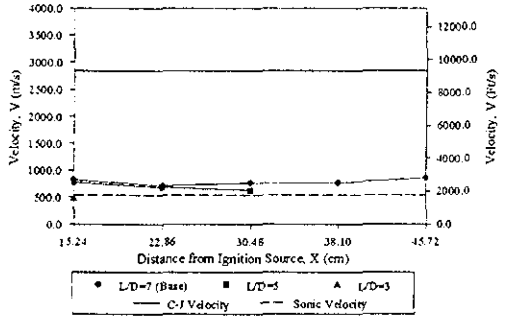

Figure 5.11: Velocity Plot for Length to Diameter Variation with H_2-O_2

The variation between the velocity plots is very small, indicating that the length of the chamber does not significantly affect the velocity of a detonation. The small effect that is noticed was due to the establishment process of the detonation. Establishment of a planar detonation wave appears to take between 15.24 cm and 22.86 cm (6-9 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. It is possible that the pre-compression phenomenon associated with the low velocity detonation reflects off of the diaphragm disrupting the development of the detonation wave.

Thrust for this set of tests is shown in Figure 5.12.

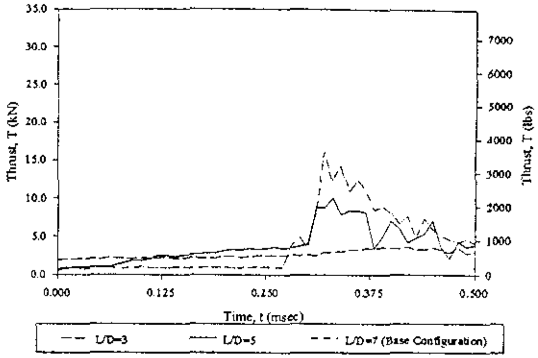

Figure 5.12: Thrust Plots for Length to Diameter Variation with H_2-O_2

Since the establishment of the detonation wave required a larger percentage of the distance in the shorter length sections, it stands to reason that the thrust would be less for the smaller length to diameter ratios which is in agreement with the test results. This particular characteristic is affected by the presence of the Mylar diaphragm as described previously.

Ignition Location

The effect due to variation of ignition location is illustrated using the wave diagram in Figure 5.13.

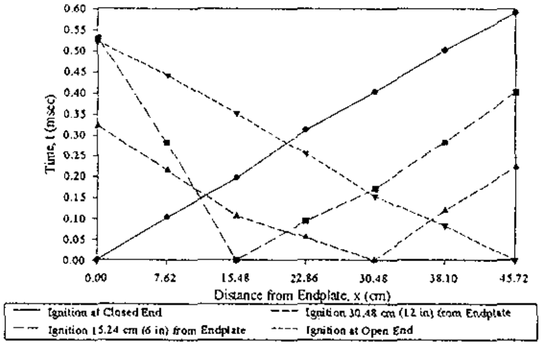

Figure 5.13: Wave Diagram for Ignition Variation with H_2-O_2

The trend to notice here is that the ignition location did not significantly affect the velocity of the detonation when it was located at either end of the chamber. However, when it was in either of the two intermediate locations the velocity of the detonation wave traveling the shorter distance was slower than the other detonation wave illustrated by the steeper slope. The wave traveling the longer distance does not encounter a barrier for the pre-compression to reflect off of as does the detonation wave traveling the shorter distance.

The thrust for these tests, Figure 5.14, shows that the thrust is maximized when the ignition is located at either end of the chamber.

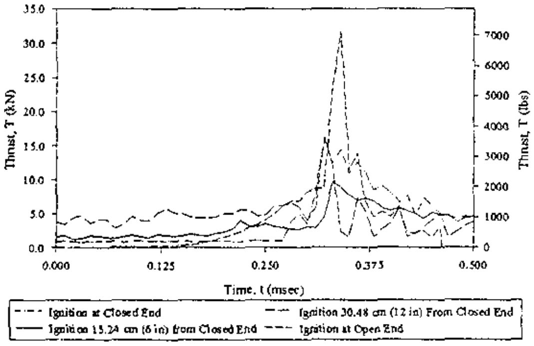

Figure 5.14: Thrust Plots for Ignition Location Variation with H_2-O_2

When the ignition is located in the middle, a large part of the thrust is not available because the detonation traveling the shorter distance never develops fully. Also, the thrust produced from the open end ignition is higher and more instantaneous. This is due to the pre-compression raising the final pressure on the shock wave as in the base configuration. The short duration is caused by the products expanding out the open end of the chamber as the shock wave travels toward the closed end.

The ignition location in the endplate also had a significant effect on the development of a detonation and subsequent transition from a low velocity to a Chapman-Jouguet detonation as shown in Figure 5.15.

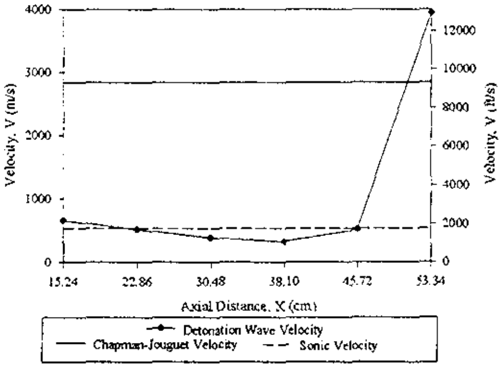

Figure 5.15: Velocity Plot of Ignition in Endplate with H_2-O_2

The reason for this is that the detonation actually had a chance to establish itself in a planar form when the ignition was in the endplate. Thus a Chapman-Jouguet detonation resulted.

Turbulence Generators

Eight turbulence generating configurations were investigated. Figures 5.16-5.18 show the velocity plots for these tests.

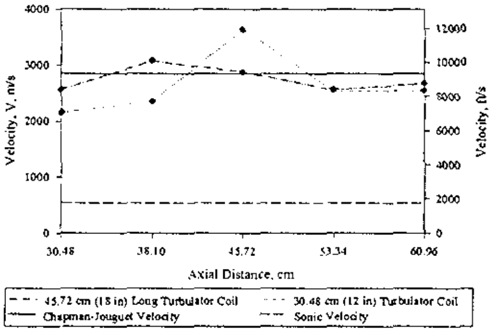

Figure 5.16: Velocity Plot of Turbulence Generators with H_2-O_2

For the turbulence coils, the velocities indicate that a Chapman-Jouguet detonation was established. This is due to the flame acceleration caused by the turbulence generator mixing the fuel and oxygen better in the boundary layer of the shock wave. As the mixing is improved the flame accelerates causing the shock wave to compensate by acceleration also. Thus a Chapman-Jouguet detonation is established.[11]

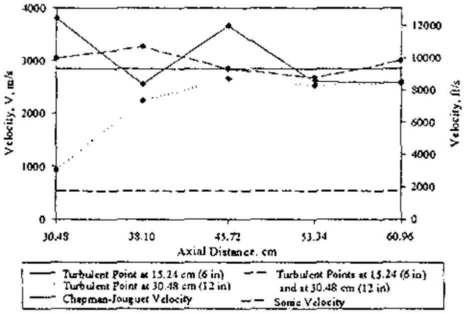

Figure 5.17: Velocity Plot of Turbulent Point Generators with H_2-O_2

When turbulent points or wire loops were used, similar results were observed. The final velocities approached the Chapman-Jouguet velocities. The flame and shock wave are allowed to re-couple because the turbulence region is localized which allows the detonation to stabilize. The turbulence points are responsible for the acceleration because the test where the turbulence point was at 30.48 cm (12 in) showed a low velocity detonation prior to the turbulence point while the test where the turbulence point was at 15.24 cm (6 in) did not.

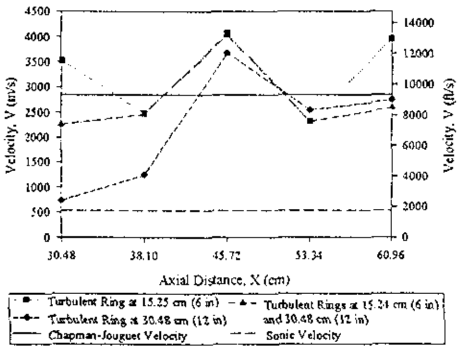

Figure 5.17: Velocity Plot for Turbulent Rings with H_2-O_2

Finally, for the ring turbulators, the velocities were found to oscillate around the Chapman-Jouguet velocity. The oscillating velocities indicate that a galloping wave was observed. This shows that larger turbulent regions prevent detonations from reaching a steady state.

Figures 5.19-5.21 show the thrust plots for the turbulence generating tests.

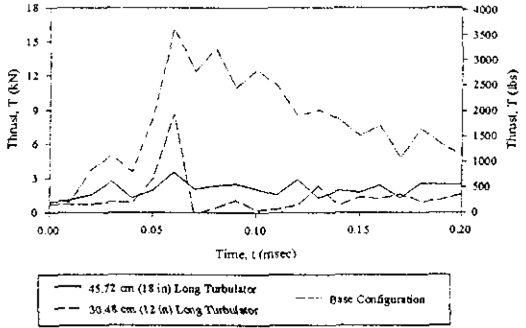

Figure 5.19: Thrust Plot for Coiled Turbulators with H_2-O_2

This plot shows that a turbulence generator in the form of a coil hinders the thrust production, especially as it is increased in length. This result agrees with the flame acceleration theory discussed in the base configuration section of the Results and Discussion. In both cases the thrust from the Chapman-Jouguet detonation was lower than the base configuration.

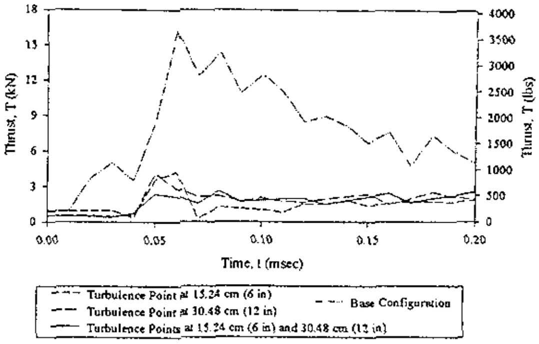

Figure 5.20: Thrust Plot for Point Turbulators with H_2-O_2

For the turbulent points, the thrust is even less than the coils produced. This is due to the fact that a low velocity detonation occurs until a turbulence generator is encountered further downstream. Supporting this is the fact that the turbulent point at 30.48 cm (12 in) produced a lower thrust than when a turbulent point was located at 15.24 cm (6 in).

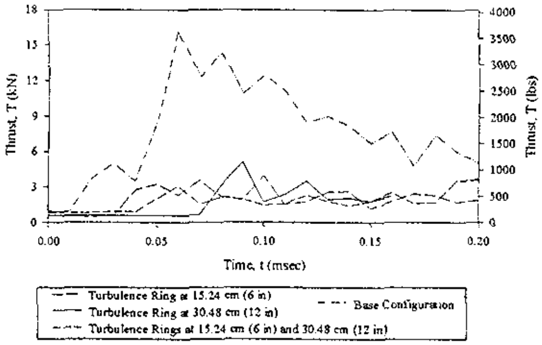

Figure 5.21: Thrust Plot for Ring Turbulators with H_2-O_2

The turbulence rings produce thrust levels comparable to the turbulent point tests which implies that the quality of the turbulence is not as important as its presence. Additionally, it appears that even though the thrust is lower for the turbulent generating devices, the sooner a Chapman-Jouguet detonation is established the higher the thrust will be. This means that the location of the turbulence is very important.

Opposing Sensors

This experiment was conducted to establish an understanding of how detonations form. Results from the length to diameter ratio variation tests implied that the detonation required 15.24-22.86 cm (6-9 in) to become established. Therefore, three pressure transducers were mounted on each side of the chamber. They were located at 7.62 cm (3 in) intervals starting at 7.62 cm (3 in) from the ignition source. Figure 5.22 shows the velocity plot for the two sets of sensors.

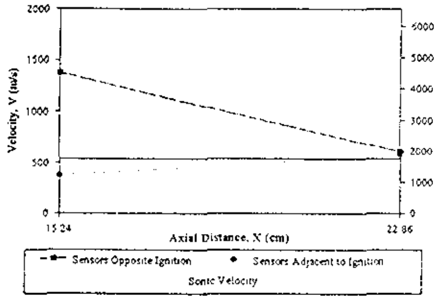

Figure 5.21: Velocity Plot of Sensors on Opposite Sides with H_2-O_2

As seen, the velocity of the detonation wave on the side opposite the ignition is faster than the that closer to the ignition. However, the two velocities do converge around 22.86 cm (9 in). This agrees with the length to diameter results implying that the establishment of the detonation wave takes between 15.24-22.86 cm (6-9 in).

Stratified Test

A set of stratified tests in which the concept of a pre-ignitor was explored was performed last. A configuration similar to the base configuration was used. The difference being that a second Mylar diaphragm was used to separate the pre-ignition section from the continuation section. The pre-ignition section was filled with a fuel and oxygen combination while the continuation section was filled with the same fuel and air. Test were conducted using both hydrogen and propane as the fuels. Figures 5.23 and 5.24 are velocity plots of two of the more successful hydrogen and propane runs, respectively.

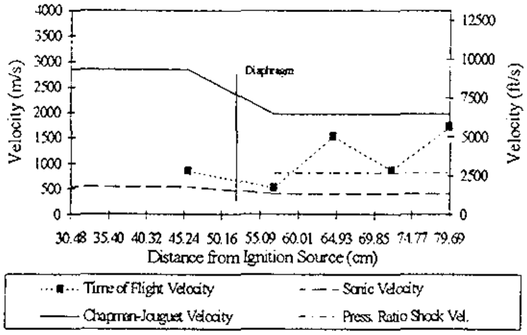

Figure 5.23: Velocity Plot for Stratified Test with H_2-O_2-Air

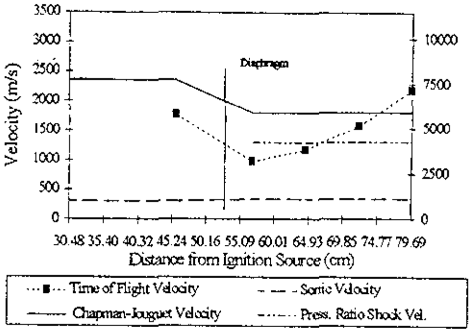

Figure 5.24: Velocity Plot for Stratified Test with C_3H_8-O_2-Air

The sensor or data point closest to the ignition source in both plots is located in the pre-ignition section and the last four point in the continuation section. The velocity in Figure 5.23 is galloping but the overall trend is an increase in the continuation section. This indicates that a Chapman-Jouguet detonation can be achieved in hydrogen and air. The propane run in Figure 5.24 produces a Chapman-Jouguet velocity near the end of the chamber in the continuation section containing propane and air. In both cases the diaphragm separating the two sections appears to momentarily disrupt the detonation as indicated by the decrease in velocity at the sensors just aft of the diaphragm, 56.83 cm (22.4 in). Also plotted on both graphs are the velocities of the shock waves that would result from the rupture of a diaphragm separating the two different sections of the chamber. This was done to illustrate that the shock wave observed in the continuation section is in fact due to a detonation and not a pressure difference.

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 probably 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. The other problem is that there is no other data to corroborate the pressure transducer data.

This made it difficult to determine what was causing the pre-compression and low velocity detonations.

Next, the data acquisition system is not capable of sampling data fast enough to observe the von Neumann Pressure Peak.[7] As Figure 6.1 shows, the error of the pressure spikes is significant when a Chapman-Jouguet detonation occurs.

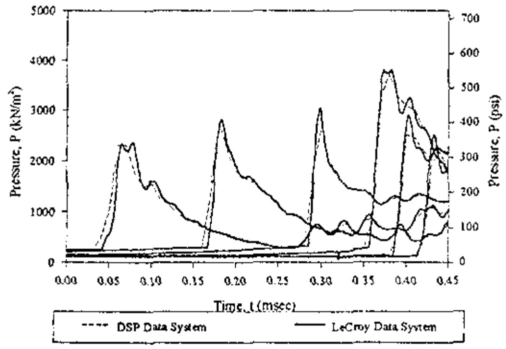

Figure 6.1: Comparison of Pressures Recorded by 2 Data Acquisition Systems with C_3H_8-O_2

However, for the low velocity detonation there appears to be only minor differences while the time index appears to agree on both plots.

Another source of uncertainty is the three dimensional effect caused by the ignition source being mounted in the side of the chamber. If a direct initiation of the detonation is occurring then the shock wave from the ignition source expands in a spherical shape. When this shock wave impinges on the end plate and on the opposite side of the chamber, several reflected shocks are created. These reflected shocks have a significant but undetermined effect on the structure and development of the detonation.

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 and thrust after the reflected shock. It also influences the development of a detonation when it is only 22.86 cm (9 in) from the ignition source. Another effect that the diaphragm has on the test program is in the stratified tests. The diaphragm absorbs some of the energy from the driving chamber and also disrupts the detonation wave structure as it passes by the diaphragm. This hampers the development of a Chapman-Jouguet detonation in the continuation section.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Several conclusions can be made from this study. The first is that the mixing of the fuel and oxidizer in this type of a propulsion system is critical for several reasons. This type of engine would be cyclic in nature, and as was shown when the fuel and oxidizer were not mixed the velocity of the detonation decreases. This would throw off the engine cycle rate and could lead to engine failure. At the very least a significant reduction in the thrust would occur.

Another conclusion is that the establishment of the detonation wave is important in thrust production. When the detonation has plenty of time to establish itself in a planar form the detonation produces much higher thrust. Because of this, ensuring the detonation establishes itself is as important as addressing the mixing problem. Related to this is the location of the ignition source. When the ignition source is at either end, the thrust production is much higher than when the ignition is near the middle, implying that the detonation energy can best be converted to thrust energy by using only one detonation wave front.

Initial pressure also affects the detonation characteristics. The cycle time cannot be decreased but the overall thrust is increased as the pressure increases. This indicates that Pulse Detonation Engines will operate more efficiently when RAM compression is used in the chamber. Static conditions, at present pose a challenge in the operation of Pulse Detonation Engines. For rocket propulsion this is very significant because a rocket chamber can be pressurized easier than an air breathing engine which means to increase the thrust, the chamber pressure simply needs to be increased.

Since a pre-compression was observed, it can be concluded that detonations exhibit unusual characteristics when forced, either by transitioning or poor fuel/oxygen mixing, to travel at velocities other than the Chapman-Jouguet velocity. This could be a sign of a lengthy transition process or a phenomenon which occurs to alleviate the forces trying to obtain a Chapman-Jouguet detonation velocity. In either case this pre-compression must be eliminated to provide dependable high frequency operation.

Hydrogen was more difficult to obtain a Chapman-Jouguet detonation than propane was which is contrary to conventional wisdom. This is accounted for by the fact that less propane was required to mix with the oxygen in the chamber than the hydrogen. Since a large volume of oxygen was mixed with a large volume of hydrogen, already in the chamber, bubbles of unmixed hydrogen and oxygen were probably created. Where with propane, only a small amount of propane was required to mix with oxygen and thus did not create unmixed pockets of fuel or oxygen. Methane behaved as expected except that it was surprising that a Chapman-Jouguet detonation was observed at all, even at an initial pressure of 3 atm.

Finally, the tests involving turbulence generators gave conflicting results. The low velocity detonation could consistently be accelerated to obtain a Chapman-Jouguet detonation, but this came at the cost of thrust. When Chapman-Jouguet detonations were established, the thrust decreased which is either due to a decrease in shock pressure or localization of the pressure rise. The thrust reduction can be minimized by using turbulent mixing devices near the ignition source. Decreasing the length of time to establish a Chapman-Jouguet detonation will increase the thrust in the chamber. It, also, is apparent that very little in the way of a turbulence generator is needed to cause the transition to occur.

Based on these results and conclusions it is obvious that several specific challenges may be met. The first challenge is the injection system. This particular challenge is partially outside the scope of this work, however, several key issues were identified which need to be kept in mind while designing the injection system. First, the fuel and oxidizer must be mixed either prior to injection or at the point of injection to ensure a Chapman-Jouguet detonation. Next is that the injection system must be tuned to operate precisely with the cycle rate of the detonations. Finally, a pre-ignition system may be required which will complicate the injection system.

Next is the ignition system. In order to make this engine viable the ignition system must be developed to a point where it will consistently produce as close to direct initiation of the detonation as possible. Additionally, since it is difficult to obtain a direct initiation of a detonation in an air mixture, the pre-ignition concept may again be needed.

Finally, obtaining a Chapman-Jouguet detonation consistently is the most important issue facing the development of this engine. To ensure that this occurs, it was shown that the low velocity detonation could be transitioned using turbulence generators, high pressure or pre-ignition. It may also be possible with a sufficiently mixed fuel and oxidizer. The best use of this conclusion would be to design the area around the ignition source as a turbulent region. For example, placing a wire mesh around the ignition location may be adequate to create the transition. However, this will probably have to be coupled with the pre-ignitor concept and mixing injection system for the air-breathing application of this engine.

To determine the best methods to use for overcoming the challenges facing this engine, further study needs to be conducted. This study should focus on the mechanisms driving the low velocity detonations and pre-compressions, which can be done by adding ionization sensors, flame detectors and sensor rakes in the chamber. Also, detailed analysis of how the detonations develop and how this is influenced by turbulence is very important to the success of this concept and should be investigated vigorously. All of these issues should be investigated in an open cycle without the diaphragm to ensure that the detonation is not effected. Finally, the ignition system appeared to work very well and should be developed to its full potential.

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