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DESIGN AND TESTING OF A DETONATION COMBUSTION
CHAMBER WITH MULTI-PORT SIDE WALL INJECTION

The members of the Committee approve the masters thesis of Peter Ping Lo

Dora Elia Musielak
Supervising Professor

Donald R. Wilson

Frank K. Lu
DESIGN AND TESTING OF A DETONATION COMBUSTION
CHAMBER WITH MULTI-PORT SIDE WALL INJECTION

by

PETER PING LO

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

December 1997
ACKNOWLEDGMENTS

I would like to acknowledge Dr. Dora Musielak and Dr. Don Wilson for giving me the opportunity and support to work on this program. The guidance they have provided has helped me tremendously during the years. I also wanted to acknowledge Jim Holland, Tom Leads, and Gene Sloan for their helpful suggestions and work on the fabrication of the experiment parts. Finally, I would like to thank Scott Stuessy for helping me along the way to designing, testing, and trouble shooting.

November 13, 1997
ABSTRACT

DESIGN AND TESTING OF A DETONATION COMBUSTION CHAMBER WITH MULTI-PORT SIDE WALL INJECTION

Publication No.____

Peter Ping Lo, M.S.

The University of Texas at Arlington, 1997

Supervising Professor: Dora E. Musielak

A detonation combustion chamber with multi-port, side wall injection was designed, fabricated, and tested. In this concept the fuel and oxidizer are injected through two rotary valves mounted 180 degrees apart, along the side walls of the cylindrical detonation test chamber. Purge air is injected through one end of the test chamber, which is regulated by a rotary disk for opening and closing. High response pressure transducers located along the side of the chamber are used for pressure measurements. Hydrogen-oxygen and propane-oxygen were used as the detonative mixtures in the chamber. A Pulse Detonation Engine operating at frequencies of up to 10 Hz was simulated in this experimental study. Recommendations for improvement are made for performance enhancement of the new detonation chamber.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .......................................................................................... iii

ABSTRACT ........................................................................................................ iv

LIST OF ILLUSTRATIONS ........................................................................... vii

LIST OF TABLES ............................................................................................... ix

CHAPTER 1. INTRODUCTION ........................................................................... 1

1.1. Historical Background ........................................................................... 1

1.2. Theory and Definition ........................................................................... 2
    1.2.1. Comparison of Deflagration and Detonation ............................... 2
    1.2.2. Detonation Phenomena .............................................................. 6

CHAPTER 2. EXPERIMENTS WITH PDE MODELS ....................................... 9

2.1. Program Overview .................................................................................. 9

2.2. Single Cycle PDE Model ....................................................................... 9
    2.2.1. Description of the Detonation Combustion Chamber .................. 10
    2.2.2. Measurement and Instrumentation .......................................... 11
    2.2.3. Tests and Results ..................................................................... 11

2.3. Low Frequency Multi-Cycle PDE Model ........................................... 12
    2.3.1. Fuel, Oxidizer, and Purge Air Injection System ....................... 13
    2.3.2. Ignition System ....................................................................... 13
    2.3.3. Results and Comparison ......................................................... 13

2.4. Summary ............................................................................................... 14
CHAPTER 3. MULTI-PORT SIDE WALL INJECTION PDE ......................... 15

3.1. Overview .............................................................................. 15

3.2. Test Facility .......................................................................... 15
  3.2.1. Design of a New Injection System .................................. 16
  3.2.2. Detonation Test Chamber ............................................. 19
  3.2.3. Instrumentation .............................................................. 21
  3.2.4. Fuel, Oxidizer, and Air Supply Lines .............................. 21

3.3. Engine Operation Procedure ............................................... 22

3.4. Problems and Solutions ........................................................ 24
  3.4.1. Electrical Noise Reduction .......................................... 24
  3.4.2. Purge Air Seal ............................................................... 25

CHAPTER 4. RESULTS AND DISCUSSION ..................................... 26

4.1. Overview of Experiments ..................................................... 26

4.2. Data Analysis ........................................................................ 27

4.3. Instrumentation Uncertainties .............................................. 40

4.4. Experimental Uncertainties ................................................ 40

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS ............... 42

APPENDIX A. EXCEL SPREADSHEET
FOR SIZING ROTARY VALVE .................................................. 45

APPENDIX B. SAMPLE LOGS OF
 ELECTRICAL NOISE REDUCTION ........................................... 49

APPENDIX C. DATA REDUCTION FORTRAN CODE .................... 52

APPENDIX D. INDIVIDUAL DETONATION PRESSURE PLOT ........ 57

REFERENCES ............................................................................. 92
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pressure versus volume cycle diagram</td>
<td>3</td>
</tr>
<tr>
<td>2. Temperature versus entropy cycle diagram</td>
<td>4</td>
</tr>
<tr>
<td>3. Rayleigh-Hugoniot Curve</td>
<td>6</td>
</tr>
<tr>
<td>4. ZND detonation wave form</td>
<td>7</td>
</tr>
<tr>
<td>5. Schematic of PDE test facility</td>
<td>10</td>
</tr>
<tr>
<td>6. Low frequency multi-cycle PDE model</td>
<td>12</td>
</tr>
<tr>
<td>7. Schematic of detonation chamber with multi-port side wall injection</td>
<td>16</td>
</tr>
<tr>
<td>8. Fuel and oxidizer injection valve shaft</td>
<td>18</td>
</tr>
<tr>
<td>9. Detonation test chamber side view</td>
<td>19</td>
</tr>
<tr>
<td>10. Detonation test chamber cross section AA</td>
<td>19</td>
</tr>
<tr>
<td>11. Detonation test chamber cross section BB</td>
<td>20</td>
</tr>
<tr>
<td>12. Injection of fuel and oxidizer</td>
<td>22</td>
</tr>
<tr>
<td>13. Arc plug ignition</td>
<td>23</td>
</tr>
<tr>
<td>14. Injection of purge air</td>
<td>24</td>
</tr>
<tr>
<td>15. Case 1 all channel pressure plots</td>
<td>30</td>
</tr>
<tr>
<td>16. Case 1 time-of-flight velocity profile</td>
<td>30</td>
</tr>
<tr>
<td>17. Case 2 time-of-flight velocity plot</td>
<td>31</td>
</tr>
<tr>
<td>18. Case 2 all channel pressure plots</td>
<td>31</td>
</tr>
</tbody>
</table>
19. Case 3 channel 1 pressure plot ................................................................. 33
20. Case 3 all channel pressure plots ................................................................. 33
21. Case 4 channel 1 pressure plot ................................................................. 34
22. Case 4 all channel pressure plots ................................................................. 34
23. Case 3 time-of-flight velocity profile .......................................................... 35
24. Case 4 time-of-flight velocity profile .......................................................... 35
25. Case 5 channel 1 pressure plot ................................................................. 36
26. Case 6 channel 1 pressure plot ................................................................. 36
27. Case 7 time-of-flight velocity profile .......................................................... 37
28. Case 8 time-of-flight velocity profile .......................................................... 37
29. Case 9 time-of-flight velocity profile .......................................................... 38
30. Case 10 time-of-flight velocity profile ......................................................... 38
31. Case 11 time-of-flight velocity profile ......................................................... 39
32. Case 12 channel 6 pressure plot ................................................................. 40
<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Quantitative differences between detonation and deflagration gases</td>
<td>2</td>
</tr>
<tr>
<td>2. Constants used for valve sizing</td>
<td>17</td>
</tr>
<tr>
<td>3. Experiment test conditions</td>
<td>26</td>
</tr>
<tr>
<td>4. Specific gravity of gases</td>
<td>27</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1. Historical Background

The feasibility of utilizing detonation combustion for aero-propulsion application has been the subject of recent investigations. Many of the complexities inherent to conventional air-breathing engines can be eliminated by using a Pulse Detonation Engine (PDE). The Pulse Detonation Engine has the potential for producing higher specific thrust and efficiency than conventional engines. A Pulse Detonation Engine operates cyclically expelling burnt gas products from the exhaust at high pressure, thus, generating thrust, without the need of the turbo-machinery required by conventional engines.

In recent decades, several pulse engine concepts have been proposed, such as those of Goddard, Bollay, Hertzberg, Logan, and Eildelman. Due to the limited knowledge of the detonation process, most of these concepts did not realistically consider initiation of a detonation, mixing of fuel and oxidizer, or transmitting the force produced by the detonation to the vehicle.

Much has been learned about detonation combustion during recent years; however, more needs to be studied in the course of developing a Pulse Detonation Engine. For propulsion applications, there is a need to develop an understanding of the interactions of
flows between pulses, the unsteady heat transfer processes, and their effect upon performance, and so on.

1.2. Theory and Definitions

In general, there are two types of flames: premixed flame and diffusion flame. A premixed flame is when reactants are perfectly mixed before chemical reaction, whereas a diffusion flame is when reactants diffuse into each other during the chemical reaction. Both deflagration and detonation are combustion waves resulting from premixed flames. The main difference between a deflagration and a detonation is the wave propagation speed. Deflagration waves propagate at subsonic speed, and detonation waves propagate at supersonic speed.  

1.2.1. Comparison of Deflagration and Detonation

Deflagration is the most common type of combustion. A stationary one-dimensional planar combustion wave can be used for analysis. The differences between deflagration and detonation are quantitatively compared in table 1.

<table>
<thead>
<tr>
<th></th>
<th>Detonation</th>
<th>Deflagration</th>
</tr>
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<tbody>
<tr>
<td>$U_1/C_1$</td>
<td>5-10</td>
<td>0.0001-0.03</td>
</tr>
<tr>
<td>$U_2/U_1$</td>
<td>0.4-0.7</td>
<td>4-6</td>
</tr>
<tr>
<td>$P_2/P_1$</td>
<td>13-55</td>
<td>0.98</td>
</tr>
<tr>
<td>$T_2/T_1$</td>
<td>8-21</td>
<td>4-16</td>
</tr>
<tr>
<td>$\rho_2/\rho_1$</td>
<td>1.7-2.6</td>
<td>0.06-0.25</td>
</tr>
</tbody>
</table>

Table 1. Quantitative differences between detonation and deflagration gases

The subscript 1 designates conditions of the unburned gases ahead of the wave, and subscript 2 indicates conditions of the burned gases behind the wave. Velocity is represented
by $U$, while $C$ is the local sonic velocity. The symbols $P$, $T$, and $\rho$ are pressure, temperature, and density, respectively. Detonation waves are supersonic and have a Mach range between five to ten. Deflagration waves, on the other hand, travel at low subsonic velocities. The pressure ratio between the burned gas and unburned gas shows that the detonation wave increases the pressure. The deflagration wave results in a slight expansion, and it is usually modeled as nearly isobaric, or constant pressure, process. A region of heat addition follows closely to both the detonation and deflagration waves, though the magnitude of heat addition for detonation is greater. Detonation wave results in an increase in density of the gas. In a deflagration, the density decreases.

The Pulse Detonation Engine cycle can be modeled as a Humphrey cycle whereas conventional engines with deflagration combustion are better described by a Brayton cycle. Figures 1 and 2 compare the two cycles. The lines connecting the points 0-1-4-5-0 represent Brayton cycle, and 0-1-2-3-0 represents the Humphrey cycle.²

---

Figure 1. Pressure versus volume cycle diagram.
The Brayton cycle, used by a deflagration-type engine, starts with a compression process from 0 to 1. It is followed by a constant pressure combustion process, or heat addition, from 1 to 4. An expansion decreases the pressure to ambient pressure (4-5). The cycle is completed when the exhaust is cooled down to ambient temperature (5-0).

The Humphrey cycle, for the pulse detonation engine, differs in that the heat addition process occurs at constant volume (1-2). It reaches a higher pressure and temperature at point 2, thus resulting in a greater thrust and higher thermal efficiency.

![Figure 2. Temperature versus entropy cycle diagram.](image)

The thermodynamic efficiencies of the Brayton cycle and Humphrey cycle are given as:

\[
\eta_{\text{Brayton}} = 1 - \frac{T_0}{T_1},
\]  

(1)
\[ \eta_{\text{HUMPHREY}} = 1 - \gamma \frac{T_0}{T_1} \left[ \frac{T_2}{T_1} - 1 \right] \frac{T_2}{T_1} - 1 \]  

The difference between these two cycle efficiencies is the ratio: \[ \gamma \frac{T_2}{T_1} - 1 \]. This term is always smaller than one; thus, the thermal efficiency of the Humphrey cycle is always greater than that of Brayton cycle. Pulse detonation engines operating on a Humphrey cycle, therefore, are said to have higher thermodynamic efficiency than conventional engines.

The thrust of an engine that operates with Humphrey cycle is also potentially higher than that of conventional engines. The thrust can be calculated from the following equation:

\[ \text{Thrust} = m_e U_e - m_a U_a + (P_e - P_a)A, \]

Where \( m = \) mass flow rate,

\( U = \) velocity,

\( P = \) pressure,

"e" represents exit condition,

"a" represents ambient condition.

With detonation combustion, the exit velocity and pressure, \( U_e \) and \( P_e \) respectively, can be much higher; therefore, the thrust created by a pulse detonation engine is potentially larger than that of conventional engines.
Other than the increase in efficiency and thrust, pulse detonation engines require less heavy machinery than conventional combustion engines. This is because compression and expansion processes in conventional engines are performed by compressors and turbines, which are not needed in a pulse detonation engine.

1.2.2. Detonation Phenomena

![Diagram]

Figure 3. Rayleigh-Hugoniot curve.

The Chapman-Jouguet theory assumes that the detonation wave is steady, planar, and one dimensional. At these conditions, Chapman and Jouguet established that the flow behind the supersonic detonation is sonic with respect to the wave front. The point on the Hugoniot curve that represents this condition is called Chapman-Jouguet point, also referred as C-J point. Points U and L in figure 3 are the tangents of Hugoniot curve and Rayleigh line.
They represent the Chapman-Jouguet (C-J) detonation point and the Chapman-Jouguet (C-J) deflagration point, respectively.

As shown in figure 3, region I is called the strong-detonation region. In this region the pressure of the burned gases is greater than that of the C-J detonation point. Region II is called the weak-detonation region. The pressure of the burned gases in this region is smaller than that of the C-J detonation point.

Extending the classical C-J theory, Zel'dovich, von Neumann, and Doring independently assumed that a flow is strictly one dimensional and steady relative to the detonation front. They postulated that the detonation wave consisted of a shock wave moving toward a gas at its initial state. The shock wave front is followed closely by a region of heat addition. Behind the detonation wave, an expansion region follows. The Zel'dovich-von Neumann-Doring (ZND) model of detonation is shown in figure 4.

Figure 4. ZND detonation wave form.
For practical purposes, it is necessary to determine whether the fuel-oxidizer mixture in the detonation chamber will undergo detonation combustion immediately or will there be a transition from deflagration to detonation. The experimental program designed for this investigation includes measurements of pressure along the chamber, to estimate the von Neumann pressure and C-J detonation pressures, and thus determine the strength of the detonation. The next chapter describes the tests that have been performed in previous programs, in order to compare with the experimental results of the present study, which is the subject of this thesis.
CHAPTER 2

EXPERIMENTS WITH PDE MODELS

2.1. Program Overview

The development of the PDE program at the Aerodynamics Research Center of The University of Texas at Arlington has evolved from the single shot to low-frequency multi-cycle tests, and then to the high-frequency multi-cycle model PDE, a part of which will be the focus of this paper. Numerous modifications have been made from model to model. To have a better view of the evolution of the PDE program, each of the previous models will be described, and results from those experiments will be discussed.

2.2. Single Cycle PDE Model

The first model of the PDE program was designed for single cycle operation only. This model consists of three parts: the cylindrical test chamber, the high-energy arc plug, and the instrumentation and data acquisition system. A schematic drawing of the PDE facility is shown in figure 5.10
2.2.1. Description of the Detonation Combustion Chamber

The test chamber is a cylindrical steel tube with three-inch inside diameter. The length of the chamber can be varied by adding different sections with the same inside diameter. One end of the chamber is closed with a steel plate, while the other end is covered by a mylar diaphragm. The arc plug is mounted on the wall of the test chamber. The location of the arc plug can be varied by shuffling the test chamber sections.

A vacuum pump empties the inside of the test chamber before fuel and oxidizer are injected through the steel endplate and filling the chamber to a desired initial pressure. The
arc plug then ignites the fuel and oxidizer mixture. A detonation wave is created; it propagates down the chamber and bursts through the mylar diaphragm to exit the chamber.

2.2.2. Measurement and Instrumentation

A series of seven PCB dynamic pressure transducers is mounted along the side wall of the chamber to monitor the detonation process in the chamber. These transducers have a range of 1,000 psi. A Baratron pressure transducer was also used to measure the ambient pressure during the testing. The measurement range of this Baratron is 10,000 Torr, or approximately 193.37 psi. The pressure transducers are connected to a DSP Technology data acquisition system, capable of 100 kHz sampling rate and a maximum of 48 channels. The data can then be retrieved by a personal computer for analysis.

2.2.3. Tests and Results

Numerous tests have been performed with the single-shot PDE model. Conclusions drawn from these tests include that length-to-diameter ratio variation of the test chamber has a very small effect on the detonation process, and mixing of the fuel and oxidizer is crucial in developing a Chapman-Jouguet detonation.\textsuperscript{11}

The variation of the test chamber geometry can be made by holding the inside diameter constant and varying the length of the chamber. By testing with different length-to-diameter ratios, it was found that the variation of detonation velocity is very small. This small effect is due to the length needed for establishment of the detonation, which is between three to six inches. As the length of the chamber decreases, this length becomes a larger part of the total length of the chamber. On the other hand, as the length of the chamber increases,
the variation in length-to-diameter ratio becomes negligible, after the detonation is fully established.

An important conclusion reached in this experiment is that the mixing of the fuel and oxidizer is crucial in achieving the Chapman-Jouguet detonation. This is further proven when turbulence generators, such as Shchelkin spirals, were used in testing. Results from these tests indicate that the turbulence generators provide a better mixing for the fuel and oxidizer. The turbulence generators can accelerate a detonation to Chapman-Jouguet velocity.\textsuperscript{12}

2.3. Low Frequency Multi-Cycle PDE Model

![Diagram](image)

Figure 6. Low Frequency Multi-Cycle PDE Model.

A multi-cycle PDE has the capability of operating continuously, with one detonation following another. The low frequency multi-cycle PDE model incorporates three rotary valves, one each for fuel, oxidizer, and purge air injection mounted on the closed end of the chamber. The purge air acts as a buffer between the burned gas mixture from one detonation and the unburned fuel and oxidizer injected for the next cycle. A complete cycle of this PDE model starts with injection of the fuel and oxidizer. It is followed by ignition of the arc plug.
The hot gas mixture is then pushed out of the chamber by purge air before another cycle starts. Cycle frequencies tested with this model range from 2 Hz to 20 Hz. A schematic drawing of this endplate injection detonation chamber is shown in figure 6.

2.3.1. Fuel, Oxidizer, And Purge Air Injection System

Three identical rotary valves were used for injection of fuel, oxidizer, and purge air. Each valve has three injection ports. These ports are lined up to the endplate of the test chamber. As the shaft of the valve rotates, these ports open and close once per revolution. The valves, rotating synchronously, are driven by a motor connected by a timing belt. The cycle frequency is solely controlled by the motor speed. This frequency is limited by how fast the valves can fill the test chamber with fuel and oxidizer.

2.3.2. Ignition System

For multiple cycle operations, an ignition system that can be controlled attuned to the injection of fuel, oxidizer, and purge air was desired. A magnetic pickup sensor was used to monitor the rotation of one of the injection valves. During each rotation of the valves, at the precise time between the injection of fuel and oxidizer and the injection of purge air, the sensor picks up a signal and triggers the arc plug to ignite. There are two capacitor banks in the ignition system, one of which discharges while the other is used to recharge the discharge capacitor bank between cycles.13

2.3.3. Results and Comparison

Initial tests without purge air were performed. One major problem was that the residual hot gas products from one cycle would ignite the fuel and oxidizer injected for the
next cycle. It, thus, created a continuous burning instead of pulses of detonations. Compressed air was then injected in between the ignition and injection of the fuel and oxidizer. This high-pressure air pushes out the hot gas before the injection process begins. Continuous pulsed detonation was achieved.

Results obtained at 2 Hz are comparable to that of the single shot. A detonation wave of peak pressure of the magnitude of nearly 100 psi was measured. A series of expansion and compression waves follow the detonation wave in both cases, as they both converge to ambient pressure over a period of time.

2.4. Summary

For a PDE to be attractive for aero-propulsion applications, a much higher operating frequency is desired. Many lessons have been learned about the detonation combustion wave, and many methods have been tried before a PDE model was actually operational. The successful testing of the two PDE models has encouraged us to continue the development of the PDE. This new PDE model will have the capability of running at frequencies up to 100 Hz. A new method of injection needs to be developed so that the test chamber can be filled faster, thus improving the potential for higher operation cycle. Mixing of fuel and oxidizer also needs to be enhanced. All these issues need to be addressed in the PDE program. A detonation combustion chamber with multi-port side wall injection will be described in chapter 3.
CHAPTER 3
MULTI-PORT SIDE WALL INJECTION PDE

3.1. Overview

A new model of the PDE was developed for capability of operation at a much higher frequency. A new test section was built for the specific use of this model. This multi-port side wall injection PDE consists of four parts: the fuel and oxidizer injection system, the test chamber, the purge air injection system, and the ignition system. The new detonation chamber employs two rotary valves, one each for the multi-port fuel and oxidizer injection configuration. These valves provide a greater volume flow rate so that the test chamber can be filled faster. A rotary disk is used for injection of the purge air through the endplate. The rotary disk rotates at the same speed as the valves to ensure the proper timing of injection. The same ignition system used for the low frequency PDE model is used.

3.2. Test Facility

The major components of this new model are the fuel, oxidizer, and air injection system. The design of this injection system is based on an operation frequency of 100 Hz. For mounting purposes, a new test chamber also was designed and fabricated. The basic cylindrical geometry of the chamber stayed the same so that it could be integrated with existing chambers. The difference in the new test chamber will be discussed in section 3.2.2.
A rotary disk was also used for injection of purge air through the end plate. Figure 7 shows a schematic drawing of the new PDE model.

![Schematic drawing of a detonation chamber](image)

**Figure 7.** Schematic of detonation chamber with multi-port side wall injection.

### 3.2.1. Design of a New Injection System

A concept of using two rotary valves for fuel and oxidizer multi-port injection was adopted. The rotary valves are mounted on the side wall of the test chamber 180° apart. With this configuration, the fuel and oxidizer impinge upon each other to promote better mixing. The basic design criterion was that, at a desired frequency, the valves can provide enough flow of fuel and oxidizer to fill the entire detonation test chamber. To design a new rotary valve for injection, the size of the test chamber must be known. For this model, the test chamber has a 3-inch inside diameter and is 16 inches long. A more detailed description of the test chamber will be given in section 3.2.2.

A Microsoft Excel spreadsheet was written to perform calculations for sizing the rotary valves. A copy of the computer program with results is shown in appendix A. The
input variables of this code include the valve shaft diameter, injection port diameter, injection pressures for fuel and oxidizer, valve rotation speed, and the total volume to be filled. Later, two variables can be fixed once the desired frequency and test chamber dimensions are determined. For a frequency of 100 Hz, with two injections per revolution of the valve, the valve speed is determined to be 3,000 RPM. The volume of the chamber can also be backed out from the three-inch diameter and 16 inch length. Some of the constants used in the Excel code are shown in table 2, where SG is the specific gravity.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>H₂ SG/Air SG at 70°F</td>
<td>0.0695</td>
</tr>
<tr>
<td>C₃H₈ SG/Air SG at 70°F</td>
<td>1.562</td>
</tr>
<tr>
<td>O₂ SG/Air SG at 70°F</td>
<td>1.105</td>
</tr>
<tr>
<td>H₂ Valve flow coefficient</td>
<td>1</td>
</tr>
<tr>
<td>C₃H₂ Valve flow coefficient</td>
<td>1</td>
</tr>
<tr>
<td>O₂ Valve flow coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Absolute temperature of flowing gas</td>
<td>540 R</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>14.7 psi</td>
</tr>
</tbody>
</table>

For example, for the condition of hydrogen and oxygen at 100 Hz and injection pressure settings of 43 psi and 100 psi, respectively, the fuel and oxidizer mixture is stoichiometric. With a rotary valve shaft diameter of 1.5 inches, and each injection port diameter of 0.3 inches, the required total number of injection ports to fill a 16-inch long test chamber is 12. This port number is, of course, dependent on the injection pressure of both the fuel and oxidizer. At operation frequency of 10 Hz and injection pressure settings of 35 psi and 70 psi, respectively, for fuel and oxidizer, only two injection ports are needed.

With the aid of this Excel code, the final size of the rotary valves was selected. Each valve has six injection ports on each side of the test chamber, for a total of 12 ports. Each
port is 0.3 inches in diameter. The valve shaft has a diameter of 1.5 inches. An actual shaft diameter of 1.491 inches was used, because that is the closed inside diameter for an off-the-shelf o-ring, which is used for sealing the two ends of the valve shaft. A drawing of the valve shaft is shown in figure 8. The bearings and timing pulley are mounted at the two ends of the shaft.

Figure 8. Fuel and oxidizer injection valve shaft.

The purge air system consists of a rotary disk with one of the covers mounted to an end of the test chamber. The other cover provides a connection to the air supply. As shown in figure 7, the rotary disk has two injection ports, each of one inch in diameter, located 180 degrees out of phase. The mounting of this purge air rotary disk aligns the ports on the central axis of the test chamber. As the disk rotates, the ports open when they are lined up with the test chamber, thus allowing high-pressure air to enter the chamber and purge out the burned gas mixtures. When the ports are closed, injection of the fuel and oxidizer occurs. The actual timing between the injection of fuel/oxidizer and purge air has to be worked out experimentally.
3.2.2. Detonation Test Chamber

The new cylindrical detonation combustion chamber is 16 inches long. The inside diameter is three inches; the outside diameter is 5.875 inches. A side view of the chamber is shown in figure 9. The cross sections AA and BB of the chamber, as indicated in figure 9, are shown in figures 10 and 11, respectively.

Figure 9. Detonation test chamber side view.

Figure 10. Detonation test chamber cross section AA.
Figure 11. Detonation test Chamber cross section BB.

The two ends of the test chamber are each welded with a steel flange that is identical to the existing flanges used on previous models. The variation of length-to-diameter (L/D) ratio can be easily done by attaching an existing chamber to the new chamber. The new chamber has seven mounting locations for pressure transducers, each spaced two inches apart from adjacent ones. The ignition arc plug can be mounted two inches from each end of the chamber. A look at figure 10 shows that the radial location of the arc plug is 45 degrees from the vertical down position of the chamber. Mounting location for seven heat flux gauges and five thermal couples are also available at 45 degrees off the vertical axis of the chamber. Seven heat flux gauge mounts are on one side, while five thermocouple mounts are on the same radial location as the arc plug mounts. This is better depicted in figures 10 and 11. The fuel and oxidizer injection ports, six of each, are located off the horizontal axis of the chamber. Longitudinally, along the wall of test chamber, each injection port is 1.1 inch apart from adjacent ones. The port nearest to the chamber closed end is located 3.9 inches away
from the endplate. The chamber has two flat surfaces, perpendicular to the injection ports, for mounting of the rotary valves.

3.2.3. Instrumentation

The same set of PCB dynamic pressure transducers model 111a24 are used in this experiment as previous models. These transducers have a response time of 1 microsecond and a useful range of 1,000 psi. Due to mechanical constraints, only six of the transducers were mounted on the chamber. The first transducer, later denoted as channel 1, is located four inches from the closed end of the chamber, while the transducer at channel 6 is located two inches from the open end of the chamber. The pressure transducers, installed in a water jacket for cooling, are flush-mounted to the interior of the test chamber to measure more accurately the detonation pressure. The pressure transducers are connected to a DSP data acquisition system. The DSP data acquisition system has a sampling rate of up to 100 kHz on 48 channels. A total of 512k samples can be taken each run. All the data are recorded on a personal computer.

3.2.4. Fuel, Oxidizer, and Air Supply Lines

For fuel and oxidizer, 1/4-inch stainless steel tubing was used. This setup can be easily reconfigured with 3/8 inch or 1/2 inch tubing, whenever necessary. Both 1/4-inch tubing and 3/4-inch tubing were used in the testing for the purge air supply line. The modification to change from one line to another is just a matter of changing a tube-fitting adapter.
The supply of gaseous fuel and oxidizer come from pressurized cylinders, while purge air comes from a high-pressure compressor. The supply pressures are monitored by regulators. In trying to maintain a constant injection pressure, an accumulator is placed at the end of each supply line, before the injection valves, to store a sufficient amount of gas required for each injection.

3.3. PDE Operation Procedure

Once the new PDE test chamber is setup, all the control switches are wired to a separate room, so that operation of the engine can be remotely controlled for safety reasons. With the motor speed set at a predetermined value, the power of the motor can be remotely turned on. As the motor turns, it drives the valves and purge disk to rotate as well. A magnetic pickup senses a signal from the sensor mounted on the motor, and in turn triggers the ignition system that ignites the arc plug. The sound of the arc sparking can be heard from

![Diagram](image)

Figure 12. Injection of fuel and oxidizer.
the control room. When the ports on the rotary valves for fuel and oxidizer are lined up with the ports on the side wall of the detonation chamber, as shown in figure 12, fuel and oxidizer are injected through these ports into the chamber. The purge air injection ports at this point are closed for injection of air through the end plate. After injection of fuel and oxidizer, the fuel and oxidizer injection ports are closed, and the ignition of the arc plug occurs. The purge air injection ports are still closed as seen in figure 13. The injection of purge air occurs when the purge air port is lined up with the end of the detonation chamber. This is after the ignition, and the fuel and oxidizer ports are still closed. This is better depicted by figure 14. The cycle repeats after that.

Figure 13. Arc plug ignition.
3.4. Problems and Solutions

Many problems were encountered since the first time setup of the new PDE model. These problems, some of electrical and some of mechanical nature, had to be eliminated, reduced, or improved to a point where the experiment could be carried out.

3.4.1. Electrical Noise Reduction

After the shakedown tests of the PDE, one significant problem was deducted from the data collected. The data taken from these runs\textsuperscript{14} has a signal to noise ratio of approximately ten percent for a signal with a peak pressure of 40 psi. For the data to hold any scientific value, this signal to noise ratio had to be improved.

Extensive tests were performed to find the sources of the electrical noise. The noise came mainly from the electrical power lines, and it was reduced by adding an isolation transformer and a power line filter in the power supply lines. Other measures of reducing
electrical noise include shielding power lines, electrical motor, and motor control unit. With all the modification made specifically to control noise, a tremendous improvement was evident as the noise level was reduced from 400 psi to approximately 8 psi. Two sample logs recorded during the time of noise reduction are shown in appendix B. The logs clearly indicate that the source of the noise came mainly from the power lines.

3.4.2 Purge Air Seal

Another problem encountered during testing, that hampered the performance of this PDE model, was due to the poor sealing of purge air on the rotary disk. The rotary disk sits inside two steel covers. The shaft of the disk passes through the bore of two bearings that were press fitted to the covers, allowing only the radial rotation of the disk. In actual practice, however, the fitting between the bearings and the shaft was not perfectly tight, thus allowing the disk to wobble as it spins. At the bottom half of the disk, where the air supply comes in from one side and goes through the other side to the test chamber, there are two seals pressed against the disk, one on each side, to prevent any air leakage. The pressure from the air and detonation wave plus the wobbling of the disk results in a high level of friction between the seals and the rotary disk. This constricts the maximum speed of the rotation of the disk, which in turn limits the frequency of the engine operation, with limited power provided by the one-horsepower DC motor.

Though it provides a very good seal, the original material selection, nitrile, creates too much friction for the motor to rotate the disk and two valves. Teflon, on the other hand, generates less friction, and at the same time provides a tolerable seal. Recommendations for further improvements will be discussed in a chapter 5.
CHAPTER 4
RESULTS AND DISCUSSION

4.1. Overview of Experiments

The data collected from this experimental program consist mainly of detonation pressure to illustrate the detonation combustion of propane and oxygen. Some tests with hydrogen and oxygen were also performed. The tests involve variation of timing, frequency, and injection pressure. Some of the data taken from the experiments are analyzed below. The test conditions for these experiments are given in Table 3. Cases 1 through 11 are tested with propane fuel. Case 12 is tested with hydrogen fuel.

Table 3. Experiment test conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Purge Air (psi)</th>
<th>Oxygen (psi)</th>
<th>Fuel (psi)</th>
<th>Frequency (Hz)</th>
<th>Combustion $\Delta P_{\text{max}}$ (psi)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>425</td>
<td>90</td>
<td>28</td>
<td>3</td>
<td>750</td>
<td>Base Line</td>
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<td>2</td>
<td>425</td>
<td>90</td>
<td>28</td>
<td>3</td>
<td>670</td>
<td></td>
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<tr>
<td>3</td>
<td>375</td>
<td>90</td>
<td>28</td>
<td>3.1</td>
<td>70</td>
<td>Injection delay 110°</td>
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<tr>
<td>4</td>
<td>375</td>
<td>90</td>
<td>28</td>
<td>3.3</td>
<td>85</td>
<td>Injection delay 130°</td>
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<tr>
<td>5</td>
<td>425</td>
<td>60</td>
<td>22</td>
<td>3.5</td>
<td>40</td>
<td>f/o=0.584</td>
</tr>
<tr>
<td>6</td>
<td>425</td>
<td>90</td>
<td>28</td>
<td>3.1</td>
<td>70</td>
<td>f/o=0.485</td>
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<tr>
<td>7</td>
<td>250</td>
<td>60</td>
<td>17</td>
<td>4.2</td>
<td>50</td>
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<td>350</td>
<td>60</td>
<td>17</td>
<td>4.2</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>425</td>
<td>60</td>
<td>17</td>
<td>3.5</td>
<td>37</td>
<td>f/o=0.505</td>
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<tr>
<td>10</td>
<td>425</td>
<td>72</td>
<td>22</td>
<td>3.5</td>
<td>46</td>
<td>f/o=0.504</td>
</tr>
<tr>
<td>11</td>
<td>425</td>
<td>77</td>
<td>22</td>
<td>3.2</td>
<td>55</td>
<td>f/o=0.476</td>
</tr>
<tr>
<td>12</td>
<td>300</td>
<td>55</td>
<td>47</td>
<td>3</td>
<td>65</td>
<td>$\text{H}_2$, f/o=0.222</td>
</tr>
</tbody>
</table>
4.2. Data Analysis

All the tests are performed in a chamber exposed to room temperature and pressure. For ease of data analysis, the temperature is assumed to be 540 R, or 80°F, and the room pressure is assumed to be 14.7 psi. The flow of fuel and oxidizer is each controlled by a regulator. A flow coefficient of 0.8 is used for the fuel and oxidizer regulator valves. With these conditions, the flow rate of a given fuel or oxidizer can be estimated by the following equation:

$$Q = 13.61 \cdot P_a \cdot C_v \cdot \sqrt{\frac{1}{SG \cdot T}}, \quad (4)$$

where $Q$ = Volume flow rate in standard cubic feet per minute,

$P_a$ = Absolute injection pressure,

$C_v$ = Flow coefficient,

$SG$ = Specific gravity of gas with respect to air,

$T$ = Temperature in Rankine.

For this application, $P_a$ is the pressure setting on the gas regulator plus room pressure. $C_v$ and $T$ are 0.8 and 540 R, respectively. The specific gravity of each gas is provided in table 3. To obtain the mass flow rate of a given gas, multiply the volume flow rate of the gas by its density.

<table>
<thead>
<tr>
<th>Gas</th>
<th>SG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.0</td>
</tr>
<tr>
<td>Oxygen($O_2$)</td>
<td>1.105</td>
</tr>
<tr>
<td>Propane($C_3H_8$)</td>
<td>1.562</td>
</tr>
<tr>
<td>Hydrogen($H_2$)</td>
<td>0.0695</td>
</tr>
</tbody>
</table>
In theory, the best performance of the PDE should occur when the fuel and oxidizer mixture is stoichiometric. The stoichiometric fuel-oxidizer mass ratio of the propane-oxygen mixture is 0.275, and the ratio for hydrogen-oxygen is 0.125. These ratios can be calculated by balancing the chemical reaction equations of each mixture, as shown in equations 5 and 6.

\[
\begin{align*}
C_3H_8 + 5O_2 & \rightarrow 4H_2O + 3CO_2 \quad (5) \\
2H_2 + O_2 & \rightarrow 2H_2O \quad (6)
\end{align*}
\]

The molecular weight of propane is 44. The molecular weight of oxygen is 32, and five oxygen molecules have a molecular weight of 160. The stoichiometric mass ratio of propane-oxygen mixture, thus, is 0.275, calculated by dividing 44 by 160. The ratio of hydrogen-oxygen mixture is calculated the same way: 4 divided by 16 yields 0.125.

A pressure setting of 90 psi for oxygen and 28 psi for propane, using equation 4, would give a fuel-oxygen ratio of 0.485. This compared to the stoichiometric ratio of 0.275 is considered fuel-rich, though many of the tests indicate that this provides the best performance of the PDE, in terms of higher peak pressure. This pressure setting for propane and oxygen was used for the base line test at 3 Hz. The quarter-inch tubing was used for purge air injection, and its pressure is set at 425 psi. The ignition arc plug was located two inches from the endplate. Injection of propane and oxygen occurred simultaneously. It was followed by ignition and purging of air. Pressure measurements were taken at six locations, starting at four inches from the endplate and ending at 14 inches from the endplate with a two-inch separation in between the transducers. These transducers, for ease of notation, were numbered as channel 1 through channel 6, with channel 1 being the one at 4 inches away from the endplate and channel 6 at 14 inches from endplate, and so on.
Individual pressure plots of a detonation wave from channels 1 through 6 of the baseline test, along with the other analyzed tests, are presented in appendix D. The vertical axis of each plot represents the absolute pressure in pounds-per-inch-square measured by the transducers. The horizontal axis is the time in millisecond. Time zero-millisecond is the time when the data acquisition system starts to record data, so it is only a reference point and has no effect on the rest of the data.

The pressure traces from all six plots indicate occurrence of a detonation wave as it travels from the closed end of the chamber to the open end. A region of precompression before the detonation wave increases the pressure from ambient condition. The sudden rise in pressure indicates the passage of a detonation wave. Following the detonation wave is a series of expansion and compression waves, which result in a sinusoidal shape of the pressure trace. The pressure plot from channel 1 shows a peak detonation pressure of 750 psi. As the wave travels down the chamber, the peak pressure gradually decreases. The peak pressure measured from channel 6 is about 320 psi. The pressure plots show that a second pressure peak follows the first peak closely. This second pressure rise is due to the reflected shock off the end plate.

The passage of the detonation wave can be better seen from figure 15, where all six channels are plotted at the same time. It is evident that the peak pressure, or detonation pressure, measured by each channel occurs at different time. Channel 1 records it first, and channel 6 measures it last. With the different time of peak pressure for each channel and the distance between channels, the velocity of the wave can be calculated. This velocity, referred to as the time-of-flight velocity, is defined by equation 7.
Figure 15. Case 1 all channel pressure plots.

Figure 16. Case 1 time-of-flight velocity profile.
\[ V_{\text{TOF}} = \frac{\text{distance}}{\text{time}}, \]  

where \( V_{\text{TOF}} \) = time-of-flight velocity,

\( \text{distance} = \) distance between two channels,

\( \text{time} = \) time a wave takes to travel from channel to channel.

For the baseline test illustrated above, the time-of-flight velocity profile is shown in figure 16. The detonation wave starts out at above CJ velocity, and then decreases to below CJ velocity, but still well above the sonic velocity.

The time-of-flight velocity profile of an identical test is shown in figure 17. This plot indicates that the velocity of the detonation wave remains fairly constant, around CJ velocity, until near the open end of the chamber, where it drops dramatically to barely over sonic velocity. The pressure trace of this test, given in figure 18, indicates a similar trend as the test discussed before. The peak pressure of the detonation starts out at 670 psi and gradually decreases to 150 psi. Again, the reflected shock from the end plate is evident from the second pressure rise.

Though two sets of identical data are taken from different tests, further attempts to repeat the test with equivalent pressure values were unsuccessful. For all the other tests, pressure peaks of only 75 psi were obtained. The inconsistency could have been the result of poor sealing of purge air and degrading of the arc plug not providing enough energy for a strong detonation.

Test results indicate that the timing of purge air injection is an important parameter in achieving higher detonation pressure. Two cases were studied with different purge air timing settings, both with the same fuel-oxidizer ratio. Case 3 purges air 110 degrees after injection.
of propane and oxygen, and case 4 purges air at 130 degrees after injection of propane and oxygen. The frequencies of the PDE are both near 3 Hz. Pressure settings are 28 psi, 90 psi, and 375 psi for propane, oxygen, and air, respectively. The peak pressure for case 3 is 70 psi at channel 1. When the purge air is delayed another 20 degrees for case 4, the peak pressure from channel 1 increases to 85 psi. The pressure traces for channel 1 of the two tests are shown in figures 19 and 21. Figures 20 and 22 are the pressure plots with combination of all channels.

![Figure 17. Case 2 time-of-flight velocity profile.](image17.png)

![Figure 18. Case 2 all channel pressure plots.](image18.png)
Figure 19. Case 3 channel 1 pressure plot.

Figure 20. Case 3 all channel pressure plots.
Figure 21. Case 4 channel 1 pressure plot.

Figure 22. Case 4 all channel pressure plots.
An observation made from figures 20 and 22 is that pressure trace at channels 1, 2, and 3 are crisscrossed. This result is seen throughout the rest of the cases, and it is suspected that this is the result of malfunctioning of the pressure transducers at these. This makes it difficult to calculate the time-of-flight velocity, because the time measurement of these pressure traces cannot be correctly obtained. The velocity at these locations can only be approximated by estimating the time between these channels. The trend of the detonation velocity can be observed from the velocity plots of cases 3 and 4 in figures 23 and 24, respectively. A general trend is that the wave starts at a high value near C-J velocity and then slows down to just about sonic speed or even below sonic speed for case 3. What causes this rapid decay of wave velocity is not known.

Figure 23. Case 3 time-of-flight velocity profile.

Figure 24. Case 4 time-of-flight velocity profile.
The effect of variation of fuel-to-oxygen ratio is demonstrated in cases 5 and 6. Case 5 has propane-to-oxygen mass ratio of 0.584. Its peak pressure at channel 1 is shown in figure 25 to be 40 psi. Case 6 has a ratio of 0.485, and its peak pressure at channel 1 is 70 psi, shown in figure 26. Variation in peak pressure is affected greatly by the change of fuel-to-oxidizer ratio.

Figure 25. Case 5 channel 1 pressure plot.

Figure 26. Case 6 channel 1 pressure plot.
Cases 7 and 8 show the effect of purge air injection variation. These velocity plots show the two waves follow the same trend. Both velocity profiles gradually die down to below the sonic velocity, but the velocity of case 8 is greater than that of case 7 at the closed end of the chamber. These detonation velocities are shown in figures 27 and 28.

Figure 27. Case 7 time-of-flight velocity profile.

Figure 28. Case 8 time-of-flight velocity profile.
Cases 9, 10, and 11 are performed at the same test conditions. Figures 29, 30, and 31 are the velocity profiles corresponding to each case, respectively. Again, the trend of each velocity profile for each case is identical, with velocity slowing down at the open end of the chamber. The magnitude of the velocity for each case, however, varies greatly. This can be contributed to the inconsistent measurements of the pressure transducers.

![Figure 29. Case 9 time-of-flight velocity profile.](image)

![Figure 30. Case 10 time-of-flight velocity profile.](image)
Finally, a case of hydrogen and oxygen is provided for comparison. The pressure level of this case, as shown in figure 32, is nearly 65 psi. It is equivalent to those of the propane. The reasons for such a low pressure measurement, like the tests with propane, can be correlated to the mounting of pressure transducers and the low level of energy provided by the arc plug. Each pressure transducer is mounted inside of a water jacket for cooling, thus when the water jacket is mounted to the detonation chamber, the transducer measurement is not reflecting the actual pressure inside the detonation chamber. The arc plug used for these tests is, at times, inconsistent in sparking. It is suspected that the energy generated by the plug was not sufficient for a high pressure, high velocity detonation. Recommendations for improvements will be given in the final chapter of this thesis.
4.3. Instrumentation Uncertainties

For the purpose of uncertainty analysis, two measurements should be taken into account. The first is the pressure measurement taken by the PCB dynamic transducers. These transducers have a $\pm 0.01$ percent full scale linearity, a $\pm 0.03\%/^\circ F$ temperature coefficient, and a $\pm 0.01$ psi resolution. The second measurement that will be used to analyze uncertainty is the distance between the pressure transducers. The uncertainty of this measurement is $\pm 0.01$ inch. The DSP data acquisition system has a resolution of $\pm 100$ nanosecond.\textsuperscript{15}

4.4. Experimental Uncertainty

The uncertainties of the pressure transducer measurements due to temperature and linearity error are given by equations 8 and 9, respectively.

$$w_T = 0.0003 \times \text{Temperature} \times \text{Pressure}$$  \hspace{1cm} (8)

$$w_l = 0.01 \times \text{Pressure}$$  \hspace{1cm} (9)
The resulting total uncertainty of the PCB pressure transducer measurements is the linear summation of all the independent uncertainties, as shown below in equation 10.

\[ w_p = 0.02 + 0.0003 \times \text{Temperature} \times \text{Pressure} + 0.01 \times \text{Pressure} \]  

(10)

For the initial pressure of one atmosphere, the hydrogen-oxygen C-J detonation temperature is 6,168°R. The uncertainty of the pressure measurement by the transducers is calculated to be 1.87 percent. For propane-oxygen at one atmosphere initial pressure, the C-J detonation temperature is 6,433°R, and the uncertainty of pressure measurement is 1.95 percent.

The uncertainty for the time-of-flight velocity calculation can be calculated from the uncertainties in distance time measurement. From equation 7, the derivatives of the velocity with respect to its independent variables, time and distance, are given in equations 11 and 12, respectively.

\[ \frac{\partial V}{\partial t} = -\frac{\text{distance}}{\text{time}^2} \]  

(11)

\[ \frac{\partial V}{\partial x} = \frac{1}{\text{time}} \]  

(12)

The total uncertainty of the velocity can, thus, be calculated by equation 13.

\[ w_v = \left[ \left( \frac{\partial V}{\partial t} w_t \right)^2 + \left( \frac{\partial V}{\partial x} w_x \right)^2 \right]^{\frac{1}{2}} \]  

(13)

where \( w_t \) is the uncertainty due to time, and \( w_x \) is the uncertainty due to distance measurement. Using this equation, the uncertainty for the time-of-flight velocity is calculated to be 12.02 percent.
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A new detonation chamber with multi-port axial wall injection was designed and fabricated, for application to a PDE which can operate at high frequencies of up to 100 Hz. This new model incorporated a new injection system that allows for a higher flow rate of gas. Preliminary testing was successful at low frequency range. The following observations and conclusions are made from this study:

1. Timing of the fuel and oxidizer injection, ignition, and purging is crucial in establishing a high peak-pressure detonation. Variation in timing is adjustable on the engine by lining up the valves and the motor at different positions. This result agrees with the results from previous tests.

2. Sealing of purge air is also very critical such that leakage of air into the chamber before ignition would dilute the fuel and oxidizer mixture thus preventing the development of a detonation wave. Teflon seals for purge air are used for operation of the PDE at frequencies up to 10 Hz.

3. With the exception of two runs, most of peak pressure measurements gathered reflect a detonation pressure of anywhere from 25 psi to 75 psi. This is somewhat lower than the data collected from previous experiments with the endplate injection PDE. The time-of-flight velocity for the side wall injection are considerably higher than that of the endplate
injection. The velocity for the side wall injection is at the magnitude of nearly Chapman-Jouguet velocity without any aid of a turbulence generator.

4. An observation made from all the pressure plots of the data is that the occurrences of the same detonation wave measured by pressure transducers at channels 1, 2, and 3 are conflicting. Again, channel 1 is located toward the close end of the chamber, while channel 6 is at the open end. As the pressure plots of a detonation wave show, the wave measured at channels 1, 2, and 3 intercross each other. At channels 4, 5, and 6, the wave behaved as expected, traveling toward the open end. This observation cannot be physically explained, as the wave cannot jump to the middle of the chamber at channel three, come back to close end at channel one, and then jump to channels 4, 5, and 6. A thorough investigation needs to be made before a scientific explanation can be made.

Several recommendations are made to improve the side wall injection PDE model:

1. The validity of the readings from the pressure transducers should be investigated, since the transducers have had a long period of experiment time and no calibration has been performed.

2. To improve quality of the data, further attempts should be made in reducing noise, though most of the electrical noises have been reduced for the experiments reported herein.

3. It is recommended to install pressure transducers in the supply lines close to injection points of fuel, oxidizer, and air, so that the amount of gases can be easily, and accurately calculated. This will help in establishing the correct consumption of gases for each cycle, at different operating conditions. This will also help to duplicate the data.
4. To operate the PDE test section at a higher frequency, the seal of the rotary disk for purge air needs to be redesigned. It is recommended to implement a spring-loaded Teflon ring to fit the existing grooves. The spring-loaded ring will provide a firm contact at the rotary disk surface, at the same time applying a minimal normal force toward the disk and reducing the friction. To stabilize the disk from wobbling, a restraint system with minimal friction is desirable. One of the options for such a system is using a face bearing on each side of the disk, between each rotary-disk cover and the disk. The bearings press against the covers and the disk tight, allowing no wobbling. The only movement allowed is the radial rotation of the disk.

5. The ignition magnetic pickup sensor trigger is another component that can be improved upon. The mounting of two metal triggers on a timing pulley are not separated 180 degrees apart. This results in a timing difference between two consecutive triggering of the ignition. During a test, if one ignition trigger is set at a desired timing in relation to injection of fuel, oxidizer, and purge air, the other trigger will be either early or late. To correct this problem, the two triggers should be mounted 180 degrees apart. During the testing, difficulty was also encountered with the inconsistent ignition of the arc plug. This results in intermittent sparking of the arc plug.

6. A more reliable arc plug needs to be developed for consistency.

7. For future experiments involving this detonation chamber with multi-port side wall injection, a new ignition system must be used with a higher frequency.

8. Instruments such as thermocouples and heat flux gauges should also be installed for additional measurements.
APPENDIX A

EXCEL SPREADSHEET FOR SIZING ROTARY VALVE
### PDE Valve Design Estimation

**Design Parameter**
- Valve shaft diameter: 1.5 in.
- Inlet diameter: 0.3 in., radius: 0.15 in., # inlet/rev.: 2

**Property**
- Oxygen: SG 1.105, Density (lb/ft³): 0.083626, Temp (R): 530, P_injection: 100 lb/in²
- Fuel: SG 0.0695, Density (lb/ft³): 0.00526, Temp (R): 530, P_injection: 43 lb/in²
- Valve Cv: 1
- Exit pressure: 14.7 psi
- Valve rotation speed: 3000 RPM
- Frequency: 100 Hz

**Test Section**
- Diameter: 3 in.
- Length: 16 in.

**Performance Calculations**
- Oxygen: Volume: 113,0976 in³
  - Mass Flow Rate: 64.50635 ft³/min
  - Volume in sec: 0.001273 sec
  - Max 2A't = 0.00009
- Fuel: Volume: 23.7231 in³
  - Mass Flow Rate: 129.3909 ft³/min
  - Volume in sec: 0.164745 ft³

**Volume Flow**
- Oxygen: 6.332516 in³
  - Total Volume: 19.03467 in³
- Fuel: 12.70216 in³

**Mass Ratio**
- O/H: 7.926407 <- Stochiometric Mix.

**Number of Injection Ports**: 11.88333

**Time** | **X** | **2A** | **2A't** | **O_2** | **H_2** | **C_3 H_8**
---|---|---|---|---|---|---
1 | 1.27E-05 | 0.0015 | 0.003227 | 4.11E-08 | 25 | 5
2 | 2.55E-05 | 0.003 | 0.004627 | 5.89E-08 | 35 | 10
3 | 3.82E-05 | 0.0045 | 0.005745 | 7.31E-08 | 45 | 15
4 | 5.09E-05 | 0.006 | 0.006723 | 8.56E-08 | 55 | 20
5 | 6.37E-05 | 0.0075 | 0.007616 | 9.7E-08 | 65 | 25
6 | 7.64E-05 | 0.009 | 0.008452 | 1.08E-07 | 75 | 30
7 | 8.91E-05 | 0.0105 | 0.009246 | 1.18E-07 | 85 | 35
8 | 0.000102 | 0.012 | 0.01001 | 1.27E-07 | 95 | 40
9 | 0.000115 | 0.0135 | 0.010749 | 1.37E-07 | 105 | 45
10 | 0.000127 | 0.015 | 0.011469 | 1.46E-07 | 115 | 50
11 | 0.00014 | 0.0165 | 0.012175 | 1.55E-07 | 125 | 55
12 | 0.000153 | 0.018 | 0.012868 | 1.64E-07 | 135 | 60
13 | 0.000166 | 0.0195 | 0.01355 | 1.73E-07 | 145 | 65
14 | 0.000178 | 0.021 | 0.014225 | 1.81E-07 | 155 | 70
15 | 0.000191 | 0.0225 | 0.014892 | 1.9E-07 | 165 | 75
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Total 2A*t 4.82E-05
Compare w/ max 2A*t 0.00009
Ratio 0.535429
APPENDIX B

SAMPLE LOGS OF ELECTRICAL NOISE REDUCTION
High Frequency Pulse Detonation Engine Experiment

July 16, 1997

After shielding the control box and relay, noise was checked again. The magnitude of the noise did not change at all. This leads all the problems to the motor.

Varying the motor speed and the results showed that at higher RPM the noise reduces considerably, as shown in table 1.

<table>
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<tr>
<th>Ignition</th>
<th>Arc</th>
<th>Motor</th>
<th>RPM Set</th>
<th>Noise</th>
</tr>
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<tbody>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>OFF(Plugged)</td>
<td>4</td>
<td>-1 → 6</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>4</td>
<td>-300 → 110</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>5</td>
<td>-250 → 70</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>6</td>
<td>-85 → 45</td>
</tr>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>7</td>
<td>-95 → 60</td>
</tr>
<tr>
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<td>OFF</td>
<td>ON</td>
<td>8</td>
<td>-160 (mostly -80) → 40</td>
</tr>
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</table>

The next step will be shielding the back of the motor, since it has big holes for airflow for the fan. The wires connecting the motor and the control box also need to be shielded.

Some copper screen needs to be ordered for shielding of the motor.
High Frequency Pulse Detonation Engine Experiment

July 17, 1997

The power lines for DAS, ignition system, and motor are filtered for noise check.

See table below for results.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Noise</th>
</tr>
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<tr>
<td>DAS was connected to Wave Tracker Filter</td>
<td>-130→50</td>
</tr>
<tr>
<td>DAS, ignition system connected to isolation transformer and Wave Tracker Filter in series.</td>
<td>-10→40</td>
</tr>
<tr>
<td>Motor power line filtered + above</td>
<td>-4→4</td>
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</table>

The noise was reduced tremendously by filtering the power lines.
APPENDIX C

DATA REDUCTION FORTRAN CODE
C PROGRAM TO GET/CONVERT/REDUCE THE TEST DATA FOR LOW SPEED
C
C 100 KHZ DATA ACQUISITION SYSTEM
C
CHARACTER*64 JUNK
CHARACTER*64 FILE(6)

CHARACTER*64 FILE01,FILE02,FILE03,FILE04,FILE05,FILE06

CHARACTER*64 V_OUT01,V_OUT02

DIMENSION CH01(87040),CH02(87040),CH03(87040),CH04(87040),
     1 CH05(87040),CH06(87040)

DIMENSION V(6,87040),PP(6)

C THE DATA FILES TO READ IN
C CHANGE THE FILE NAME FOR EACH RUN

OPEN(4,FILE="DATAFILE.DAT",STATUS="OLD")

DO 500 I=1,6
  READ(4,400)FILE(I)
400   FORMAT(A12)
    IF(EOF(4)) GO TO 501
500   CONTINUE

501   FILE01=FILE( 1)
       FILE02=FILE( 2)
       FILE03=FILE( 3)
       FILE04=FILE( 4)
       FILE05=FILE( 5)
       FILE06=FILE( 6)

C OPEN THE FILES NEEDED IN THIS PROGRAM
OPEN(11,FILE=FILE01,STATUS="OLD")
OPEN(12,FILE=FILE02,STATUS="OLD")
OPEN(13,FILE=FILE03,STATUS="OLD")
OPEN(14,FILE=FILE04,STATUS="OLD")
OPEN(15,FILE=FILE05,STATUS="OLD")
OPEN(16,FILE=FILE06,STATUS="OLD")

C USER INTERFACE FOR KEYIN OUTPUT FILE NAME AND RANGE
WRITE(*,10)

WRITE(*,'(A)') ' ENTER THE VOLTAGE OUTPUT FILE NAME : '
READ(*,'(A)') V_OUT01
WRITE(*,'(A)') ' ENTER THE VOLTAGE TEST WINDOW FILE NAME : '
READ(*,'(A)') V_OUT02
WRITE(*,10)

10 FORMAT(1X,/) 

OPEN(5,FILE=V_OUT01,STATUS='UNKNOWN')
OPEN(6,FILE=V_OUT02,STATUS='UNKNOWN')

C DUMP THE FIRST 3 LINES IN THE DATA FILE
DO 100 I=1,3
   READ(11,*JUNK ! 001
   READ(12,*JUNK ! 002
   READ(13,*JUNK ! 003
   READ(14,*JUNK ! 004
   READ(15,*JUNK ! 005
   READ(16,*JUNK ! 006
100 CONTINUE

C READ IN DATA FROM EACH INPUT FILE
H = 1
N = 87040/8
DO 200 I=1,N

   IF(EOF(11)) GO TO 203

   READ(11,*)(CH01(J), J=H,H+7)
   READ(12,*)(CH02(J), J=H,H+7)
   READ(13,*)(CH03(J), J=H,H+7)
   READ(14,*)(CH04(J), J=H,H+7)
   READ(15,*)(CH05(J), J=H,H+7)
   READ(16,*)(CH06(J), J=H,H+7)
   H = H + 8

200 CONTINUE

C CONVERTING THE OUTPUT SIGNAL TO VOLTAGE

C PRESSURE TRANSDUCER CALIBRATION

C Ch NUMBER 0-1000PSI(mV/PSI) 0-100PSI((mV/PSI)
C  1   8266  4.91   4.90  C
C  2   8267  4.97   4.95  C
C  3   8265  4.88   4.82  C
C  4   8264  4.74   4.72  C
C  5   8263  5.15   5.16  C
C  6   8262  5.01   5.00  C

203  DO 1001 K=1,87040
     V( 1,K) = 5./(4095.-2048.)*(CH01(K)-2048.0) * 1/0.00491 / 1
     V( 2,K) = 5./(4095.-2048.)*(CH02(K)-2048.0) * 1/0.00497 / 1
     V( 3,K) = 5./(4095.-2048.)*(CH03(K)-2048.0) * 1/0.00488 / 1
     V( 4,K) = 5./(4095.-2048.)*(CH04(K)-2048.0) * 1/0.00474 / 1
     V( 5,K) = 5./(4095.-2048.)*(CH05(K)-2048.0) * 1/0.00515 / 1
     V( 6,K) = 5./(4095.-2048.)*(CH06(K)-2048.0) * 1/0.00501 / 1

1001  CONTINUE

C  PRESSURE OFFSET
C  OMIT FIRST 10 PTS, THEN TAKE THE NEXT 100 DATA PTS

DO 701 I=1,6
 PP(I) = 0.0
     DO 111 J=10,110
      PP(I) = PP(I) + V(I,J)
     CONTINUE
701  CONTINUE

DO 702 I = 1,6
 PP(I) = PP(I) / 100
     DO 112 J = 1,87040
      V(I,J) = V(I,J) - PP(I)
112  CONTINUE
702  CONTINUE

C  OUTPUT THE TRANSFORMED FILE
 TIME01 = 0.0
 DO 1002 L=1,87040
 WRITE( 5,201)TIME01,(V(K,L)+14.7,K=1,6)
 TIME01 = L * 0.01
201  FORMAT(1X,F10.6,6(2X,F10.4))
1002  CONTINUE
WRITE(*,*) "ENTER THE TEST WINDOW START TIME T1 : (XXX00)"
READ(*,*) IT1

IT2 = IT1 + 3000

DO 1005 L = IT1, IT2
    TIME = L * 0.01
    WRITE(6,302) TIME, (V(K,L)+14.7, K=1,6)
302 FORMAT(1X,F10.4,6(2X,F10.4))
1005 CONTINUE

STOP
END
APPENDIX D

INDIVIDUAL DETONATION PRESSURE PLOTS
CASE 1
(Propane-28 psi, Oxygen-90 psi, Air-425 psi, 3 Hz)
CASE 2
(Propane-28 psi, Oxygen-90 psi, Air-425 psi, 3 Hz)
CASE 3
(Propane-28 psi, Oxygen-90 psi, Air-375 psi, 3.1 Hz)
CASE 4
(Propane-28 psi, Oxygen-90 psi, Air-375 psi, 3.3 Hz)
CASE 5
(Propane-22 psi, Oxygen-60 psi, Air-425 psi, 3.5 Hz)
CASE 6
(Propane-28 psi, Oxygen-90 psi, Air-425 psi, 3.1 Hz)
CASE 7
(Propane-17 psi, Oxygen-60 psi, Air-250 psi, 4.2 Hz)
CASE 8
(Propane-17 psi, Oxygen-60 psi, Air-350 psi, 4.2 Hz)
CASE 9
(Propane-17 psi, Oxygen-60 psi, Air-425 psi, 3.5 Hz)
CASE 10
(Propane-22 psi, Oxygen-72 psi, Air-425 psi, 3.5 Hz)
CASE 11
(Propane-22 psi, Oxygen-77 psi, Air-425 psi, 3.2 Hz)
CASE 12
(Hydrogen-47 psi, Oxygen-55 psi, Air-300 psi, 3 Hz)
REFERENCES


92
