Abstract

ORDON, ROBERT LEWIS. Experimental Investigations Into The Operational Parameters Of a 50 Centimeter Class Pulsejet Engine. (Under the direction of Dr. William L. Roberts.)

A hobby scale pulsejet, commercially available from Bailey Machine Services (BMS), is significantly instrumented and tested to develop a theoretical understanding of how various inlets, fuel systems, and exhaust sizes effect the overall performance of the jet. The purposes of these experiments are to aid in the development and optimization of valveless pulsejet engines. A valved inlet running on ethanol is tested as well as valveless inlets running on propane. Valveless inlet diameters and lengths are varied as well as exhaust lengths and compared to acoustic models, namely the Helmholtz resonator and 1/6 wave tube resonator models. Temperatures, average and peak combustion chamber and exit pressures, sound pressure levels and jet operating frequencies were recorded at various fuel flow rates.
EXPERIMENTAL INVESTIGATIONS INTO THE OPERATIONAL PARAMETERS OF A 50 CENTIMETER CLASS PULSEJET ENGINE

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Biography

The author was born Robert Lewis Ordon of Pensacola, Florida in May of 1977, son of Ramon and Mary Ordon. He is the youngest son with a half-brother and half sister, Howard and Elisa. At age 3 he and his mother moved to Plainsboro, New Jersey. There his mother married Bruce Meyers. He was enrolled in the West Windsor – Plainsboro school system until graduating from West Windsor Plainsboro High School in May of 1995.

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Immediately after receiving his degree, Robert took a job in Washington, DC where he worked as a scientific advisor for program managers at the Defense Advanced Research Projects Agency (DARPA). It was while working on various programs at DARPA that Robert decided that he wanted to further his technical education.

Following the deaths of both of his biological parents in late 2002, he decided to return to school and enter the Masters of Science program for Mechanical Engineering where he received his degree under the direction of Dr. William L. Roberts.
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Table of Contents

1. Introduction ..............................................................................................................................1
   1.1 Background and History ................................................................................................1
   1.2 Related Work ............................................................................................................. ..8
   1.3 Pulsejet Cycle ............................................................................................................. ..10

2. Experimental Apparatus and Setup .....................................................................................13
   2.1 Pulsejets .................................................................................................................. .....13
      2.1.1 Bailey Machine Service Valved Jet ......................................................................13
      2.1.2 Valveless Jet ......................................................................................................14
   2.2 Cooling System ............................................................................................................15
   2.3 Inlets ..................................................................................................................... ........16
   2.4 Fuel Delivery .............................................................................................................. .17
   2.5 Ignition System ............................................................................................................18
   2.6 Pressure Measurements ...............................................................................................19
   2.7 Thermocouples .............................................................................................................21
   2.8 Sound Pressure Level Meter ........................................................................................22
   2.9 Thrust Stand .................................................................................................................23
   2.10 Procedures ................................................................................................................ ....23
      2.10.1 Starting of the Jet ..........................................................................................23
      2.10.2 Data Collection .............................................................................................24

3. Parametrics / Performance ...................................................................................................25
   3.1 BMS Valved Tests .......................................................................................................25
   3.2 Valveless Tests ..............................................................................................................28

4. Helmholtz Resonators and Quarter Wave Tubes ...............................................................49
   4.1 Helmholtz Resonators .................................................................................................49
   4.2 Quarter-wave Tubes .....................................................................................................49

5. Sound Pressure Levels ...........................................................................................................56

6. Conclusion ..............................................................................................................................58

7. Future Work ...........................................................................................................................59

References .....................................................................................................................................60
List of Figures

Figure 1–1: Schematic of Vapor Pulsejet ‘Pop-Pop’ Boat .........................................................2
Figure 1–2: Marconnet Valveless Engine ..................................................................................3
Figure 1–3: German V-1 ‘Buzz Bomb’ Pulsejet Powered Cruise Missile ..................................4
Figure 1–4: U-Shape Pulsejet ..................................................................................................7
Figure 1–5: Escopette valveless pulsejet ...............................................................................9
Figure 1–6: Fuel Injection Location ......................................................................................10
Figure 1–7: Lenoir Cycle ......................................................................................................11
Figure 1–8: Humphrey Cycle ..............................................................................................12
Figure 2–1: Standard BMS Pulsejet ......................................................................................13
Figure 2–2: Dimensions of Experimental Jet .........................................................................14
Figure 2–3: Ports with Water Jackets added to BMS Jet ........................................................16
Figure 2–4: First Set of Steel Inlets ......................................................................................16
Figure 2–5: Hastings Model 40 Flow Meter ..........................................................................17
Figure 2–6: Fuel Injector Installed in Jet ...............................................................................18
Figure 2–7: Nichrome Ignition (top) and Spark Ignition (bottom) ........................................19
Figure 2–8: Mercury Manometer .........................................................................................20
Figure 2–9: Completed Type-B Thermocouple ....................................................................21
Figure 2–10: Taylor Model 9841 Thermometer ..................................................................22
Figure 2–11: Radio Shack SPL Meter ...................................................................................22
Figure 3–1: CH* vs. Combustion Chamber Pressure ............................................................26
Figure 3–2: Pressure Plot for Valved Jet ...............................................................................27
Figure 3–3: Valved Jet Temperature vs. Time ......................................................................27
Figure 3–4: Lower Throttleability Limit for Various Extension Lengths ......................31
Figure 3–5: Lower Throttleability Limits for Various Inlets ..............................................32
Figure 3–6: Upper Throttleability for Various Extension Lengths ................................33
Figure 3–7: Upper Throttleability for Various Inlet Diameters ........................................33
Figure 3–8: Temperature vs. Exhaust Length for ½” Inlet (3” Long) .................................34
Figure 3–9: Temperature vs. Exhaust Length for ½” Inlet (2” long) .................................35
Figure 3–10: Temperature vs. Exhaust Length for 5/8” Inlet .............................................36
Figure 3–11: Temperature vs. Exhaust for 7/8” Inlet ..........................................................36
Figure 3–12: Temperature vs. Exhaust Length for 1” Inlet ...............................................37
Figure 3–13: Jet Temperatures vs. Inlet Diameter +3” Extension, 3” Long Inlet ...............38
Figure 3–14: Jet Temperatures vs. Inlet Diameter +6” Extension, 3” Long Inlet ...............38
Figure 3–15: Jet Temperatures vs. Inlet Diameter +9” Extension, 3” Long Inlet ...............39
Figure 3–16: Throttleability Ranges for Various Inlets at Various Extension Lengths ......40
Figure 3–17: Operational Envelope based on Inlet and Exhaust Length ..........................41
Figure 3–18: Throttleability Ranges for Various Extension Lengths with Various Inlets ....41
Figure 3–19: Operating Frequency as a Function of Exhaust Length for Various Inlets ...42
Figure 3–20: Operating Frequency as a Function of Various Inlets at Various Exhaust Lengths 43
Figure 3–21: Change in Port 1 Pressure vs. Inlet Diameter ...............................................44
Figure 3–22: Average Port 1 and Port 3 Pressure vs. Inlet Diameter ..................................45
Figure 3–23: Average Port 1 and Port 3 Pressure vs. Exhaust Extension Length ..............46
Figure 3−24: 2nd Harmonic Visible in Exhaust Frequency for 1” Inlet ........................................47
Figure 3−25: 2nd Harmonic Visible in Exhaust Frequency for 1/2” Inlet .....................................47
Figure 4−1: Actual vs. Modeled Frequencies for 5/8” Inlet ..........................................................51
Figure 4−2: Actual vs. Modeled Frequencies for 7/8” Inlet ..........................................................51
Figure 4−3: Actual vs. Modeled Frequencies for 1” Inlet .............................................................52
Figure 4−4: Actual vs. Modeled Frequencies as a function of Inlet Diameter for 3” Exhaust .........53
Figure 4−5: Actual vs. Modeled Frequencies as a function of Inlet Diameter for 6” Exhaust .....53
Figure 4−6: Actual vs. Modeled Frequencies as a function of Inlet Diameter for 9” Exhaust .....54
Figure 5−1: SPL vs. Inlet Diameter for Various Lengths .................................................................56
Figure 5−2: SPL vs. Extension Length for Various Inlets ...............................................................57
List of Tables

Table 3–1: Overall Test Results ............................................................................................. 29
Table 4–1: Actual Frequency Compared to Calculated.......................................................... 55
1. **Introduction**

The investigation into pulse combustion engines was initially funded by the Defense Advanced Research Projects Agency (DARPA) to explore the scalability of such engines, particularly for small Unmanned Aerial Vehicle (UAV) propulsion. The design parameters of pulsejets had not been fully investigated and equations have not been developed to scale such jets in a highly predictable manner. Deciphering the scaling laws and dominant design characteristics of the jets in order to have a tool for optimization of the engines was a primary objective of this work.

1.1 **Background and History**

The concept of the first pulsed jet can be traced back to an 1882 Publication by Nikolai Egorovich Zhukovsky. His paper, ‘On the reaction force of in-and-out oscillating flowing liquid’, is the first reference to the ‘Vapor Pulse Jet’. The subject of the paper was developed in two subsequent editions published in 1885 and 1908. Stating a general method used for the determination of the motion of a body and fluid inside it, he investigated Helmholtz’s problem and augmented it by the new problem of the motion of a closed tube filled with fluid. He studied this last problem with the aid of the theory of pipes of Poiseuille, and its solution was verified by a special experiment performed by him (Zamyatina, 1986).

In 1891 and 1898 Désiré Thomas Piot obtained British Patents for powering model boats called ‘Pop-Pop’s’. As seen in Figure 1−1, a vapor pulse jet has two main parts: A small flash boiler, ‘d’, connected to small diameter condenser tubes. The boiler is filled with water through the tube opening, ‘h’. It is then placed in some water reservoir and some source of heat is placed under the boiler, ‘c’. Once the boiler gets hot enough, it flash boils the water. This increase in pressure forces the boat forward by forcing water out of the pipes.
The pressure then drops due to an over expansion and the water returns up the tube with just enough spilling in to the boiler to flash boil again (Piot, 1898; Le Bot, 2005).

Since 1891, millions of these simple toy boats have been produced. Piot boats are known to have been originally available from A.W.Gamages, London in 1891. Simple experiments with this boat showed that the operating frequency was dependant on the length of the water pipes. Performance varied with the shape of the boiler, but no significant scientific measurements had been taken (Science, 2005).
Nine years later, in 1906, Russian engineer Vladimir V. Karavodin experimented with pulsejets in basic research to find the effects of varying tube length and diameter had on the cycle pulse frequency, stability and thrust produced. The jet tube he used was straight and of constant diameter. He obtained a patent for an air breathing pulse-jet engine. In 1907 he built a working engine based on his invention (Gwynn, 2005). Basically the system produced a high velocity pulsed gas jet generated by a cyclic combustion of a liquid hydrocarbon fuel / air mixture.

French scientist Marconnet followed in 1909 with an air intake volume controlled with conical expansion nozzle at the jet thrust output seen below in Figure 1−2 (Reynst, 1961).

The most infamous pulsejet was developed by German Paul Schmidt (Foa, 1960; Reynst 1961) in conjunction with a German manufacturer, Argus, in 1939. That pulsejet used a series of one-way valves at the intake end of the tube to intake a fresh volume of air to mix with the atomized fuel prior to ignition. This jet was used to power the V-1 “Buzz Bomb” shown in Figure 1−3. The V-1 had a mass of 4750 lbs and produced 650 lbs of thrust at an altitude of 3000 ft and at a cruise speed of 400 mph (Reynst, 1961; Zaloga, 2005). Once the motor had reached operating temperature and had been accelerated to minimum air flow velocity ( launched using a steam catapult ) the air / fuel pulsejet no longer needed its
electrical ignition system and continued to run thanks to reflected pressure waves from the jet output nozzle that opened the valves, compressed the new intake charge, and ignited it.

![German V-1 'Buzz Bomb' Pulsejet Powered Cruise Missile](image)

Figure 1-3: German V-1 ‘Buzz Bomb’ Pulsejet Powered Cruise Missile

The reliability of V-1 jets was very good and directly related to the simplicity of the design and the minimum number of working parts. The statistical chance of something breaking or failing to function increases with the number of components and the complexity of the system. Plus since these were expendable, a cheap technology was desirable. The V-1 pulsejet was first used as a weapon against England on the 13th of June 1944 one week after the start of the D-Day allied invasion and thus became the first cruise missile (Zaloga, 2005).

Despite the V-1’s limitations, the US military was very interested in its capabilities. In July 1944, captured V-1 components were shipped to Wright-Patterson Field in Ohio for
evaluation. Within three weeks, the USAF had built their own V-1, which was designated the "Jet Bomb 2 (JB-2)" (Goebel, 2005).

In August of 1944, the USAAF placed an order for 1,000 JB-2s, these JB-2s’ had an improved guidance system when compared with that of the V-1. Ford built the PJ-31 pulse-jet engine and Republic built the airframe. Other manufacturers built the control systems, launch rockets, launch frames, and remaining components. At the end of World War II there were parallel development programs undertaken in Russia, France, and the United States to produce new pulsejet rockets (Goebel, 2005).

The JB-2s were launched off of a rail with a solid rocket booster, compared to the steam catapult system that the Germans used. The USAF then experimented with air-launching the JB-2. Most of the launches were from a B-17 bomber, though some were performed from B-24s and B-29s. The Air Force was so enthusiastic with the results that they increased the order for JB-2s to 75,000 in January 1945. However, the end of the war in August dampened enthusiasm for the weapon, and the program was terminated in September of that year. 1,200 JB-2’s had been built (Goebel, 2005).

The US Navy also experimented with its own V-1 variant, the "KUW-1 Loon". The Loon weighed 5000 lbs and cruised at 425 mph. Two submarines, the USS Carbenero and the USS Cusk, and a surface vessel, the USS Norton Sound, were modified to launch the KUW-1. In February 1947, the Cusk successfully launched a Loon (Goebel, 2005). The flying bomb was stored in a watertight hanger on the deck of the submarine, and assembled and launched by solid rocket boosters while the submarine was on the surface. Today the US Navy uses Tomahawk cruise missiles in a similar manner; however they are stored in torpedo tubes or converted ballistic missile tubes.
The Russians are also believed to have built copies of the V-1, and the French operated a target drone based on the V-1 and designated the "Arsenal 5.501" well into the 1950s, though it differed from the original design in having twin tailfins and was radio controlled (Goebel, 2005).

After World War II was over, there were many new engines to choose from. The jet age was born. Pulsejets were placed on the shelf as the gas turbine engine took over due to its reliability and significantly better specific fuel consumption. While the race to the moon was nearing an end, there was a desire for jetpacks and hovering vehicles. Lockwood and Hiller performed a small study on the jets.

The Lockwood-Hiller design, a valveless variant, was patented in 1963 (Lockwood, 1963). This variant works off of the same principles of the Marconnet design, however the tube was bent into a U-shape to have thrust going in the same direction from both the inlet and exhaust. An example of this can be seen in Figure 1–4.
The advantage of the Lockwood design is its simplicity, with no moving parts, and low production cost. With the use of thrust augmenters, sleeves that use the unsteady operation of the jet to draw in more air and thus increase the mass flux, 9:1 thrust to weight ratios have been claimed.

However, despite this advantage, pulsejets are currently not considered to be a practical power plant due to their high fuel consumption, low efficiency, and very high noise levels. Model pulsejets were produced by Jet Dyne in the US just after the war and called the Dyna Jet 1. That engine produced 5 lbs of thrust. Today a company called Bailey Machine Services (BMS) produces a relatively identical pulsejet model for airplane modelers and hobbyists with the same thrust figures; both are valved models.
Pulsejet engines are generally characterized by extreme simplicity, low cost of construction, high reliability, poor fuel economy and very high noise levels. The high noise levels make them impractical for applications other than military. However efforts have been made to reduce these levels. Pulsejets have been used to power tip-driven experimental helicopters. With the engines attached to the extreme ends of the rotor blades they have the benefit of not producing the usual reaction torque upon the fuselage, thus the helicopter may be built without a tail rotor and its associated complexity and weight, greatly simplifying the aircraft. Pulsejets have also been used in both tethered as well as radio-control aircraft. Even with all of these achievements, not much research has gone in to the optimization and understanding of the fundamentals of pulsejet operations.

1.2 Related Work

In 1949, Cornell Aeronautical Laboratory was working on a project for the US Navy, called Project Squid. The focus of the report was to investigate the operation of valveless pulsejets. The jets they used are of similar size to that of the experiments performed in this work. The difference being that the jet was fed a metered amount air, which allowed for the calculation of thrust. They experimented with different fuels and injection methods. Methane turned out to be the best fuel to use since it was already in gaseous form and did not have to overcome the latent heat of vaporization; it also performed better than propane in some situations. Various tail lengths were tested as well as exit configurations. A commercially available, liquid fueled, valved version was tested for comparative results. They then tried to convert it to propane and were unsuccessful. Tailpipe lengths were varied and showed that there was a minimum TSFC reached at 16 inches in exhaust length for that configuration. They also note that there were some intermediate lengths were resonance was
not achievable. Since both fuel and air were controlled, mixture fractions were also
controlled, it was found that at the lean limit, the pressure was higher, yet the frequency was
lower (Logan 1951).

In October of 1951, Raymond Bertin analyzed an Escopette pulsejet shown in Figure 1–5. An Escopette pulsejet is similar to a Marconnet pulsejet in that it has no valves, and
instead, uses an ‘air diode’ to control the fluid. According to their research of the 1950’s, the
inlet has no preferred frequency; this along with its high reliability and ease of using constant
fuel pressure for feeding made it very attractive. Unfortunately the ‘air diode’ also allows air
to flow back out of it, thus reducing thrust so a 180° bend was placed at the front (Bertin,
1951).

![Figure 1–5: Escopette valveless pulsejet](image)

The American Helicopter Company tried to use pulsejets as tip-propulsion for rotors,
thus relaxing the need for an anti-torque tail rotor. Tests were performed at various altitudes
and noise tests were conducted as well. They found that as the altitude was increased and
density decreased, the jet became more and more difficult to start. All data was converted to
‘standard data’ for comparison purposes. As suspected, a decrease in thrust was noted as air
density decreased (Emmerich, 1953).
In 1963, Hiller Aircraft Company looked into U-Tube pulsejets. They experimented with many ways to increase thrust as well for the purpose of making a lightweight engine. They tested several exit geometries and combustion chamber designs. They found that changing the combustion chamber shape had a dramatic effect on thrust and efficiency with TSFC levels less than 2.0 pph/lb. Small inlet lips showed the best results, whereas large bell mouth inlets did not work that well. They found that fuel injection worked best inside the combustion chamber next to the edge of the diverging section, shown below in Figure 1–6, as ‘B (Lockwood, 1963)’.

![Figure 1–6: Fuel Injection Location](image)

1.3 Pulsejet Cycle

A pulsejet’s operation can be explained by combining two-cycles: the Lenoir Cycle which consists of isentropic compression followed by constant volume heat addition and then adiabatic expansion and the Humphrey Cycle, which operates similarly but has an isentropic compression added to the cycle. Pulsejets typically have a very small compression ratio that
reaches a maximum at around 1.7. The Lenoir three cycle process can be seen below in Figure 1–7.

Figure 1–7: Lenoir Cycle

The process consists of the intake of air and fuel at point a, isochoric combustion from a to b, and an adiabatic expansion to c. The Humphrey Cycle is shown below, Figure 1–8 and adds a small amount of compression before combustion, step a to b. This holds true for both valved and valveless models.
Figure 1–8: Humphrey Cycle
2. Experimental Apparatus and Setup

The goal of these experiments was to determine the effects of different inlet diameters as well and inlet and exhaust lengths on valveless jet performance. The fuels used in these experiments were liquid ethanol and gaseous propane. Starting with liquid in the valved engine was a good point of departure because this is the conventional configuration. Modifications were then made to test a valveless version and the fuel was switched to propane for simplicity as well as superior mixing qualities due to the propane being a gaseous fuel. Since the jet's purpose was to be involved in computational modeling as well as scaling down, propane was a logical choice.

2.1 Pulsejets

2.1.1 Bailey Machine Service Valved Jet

A BMS pulsejet, Figure 2−1, was purchased as an off-the-shelf model and then modified and instrumented for temperature and pressure measurements.

![Figure 2−1: Standard BMS Pulsejet](image)

Initially, ports were placed on the jet at three different axial locations. These access ports were designed to allow for connection of thermocouples as well as pressure transducers to monitor the jet’s behavior at separate locations during operation. The locations chosen
were right behind the valve face, after the converging section, and at the exit plane. Later, two more ports were added to determine where combustion was taking place as shown in Figure 2−1. One was placed at the end of the combustion chamber, and the other half way down the exhaust tube. These access ports needed to be cooled due to the high speed pressure transducers sensitivity to temperature, so copper tubing was wrapped around them and water was forced through it. Cooling seemed to be adequate. The jet was then cut 1 ¾” from the tip of the exhaust so that extensions could be added to increase the length. This was necessary due to the flaring at the tip. This was done to allow assessment of the jet’s performance at different lengths. Another data port was placed on the flared tip right before the flare so that it was possible to collect exit pressure and temperature data.

2.1.2 Valveless Jet

Five valveless heads were then made, out of aluminum, with different diameters (1/2”, 5/8”, 7/8”, 1”, 1 ¼”) to see if valveless operation would be possible and at what lengths. Aluminum was chosen because it was available and was an easy material to machine. A fuel injection port, denoted as ‘F.I.’ in Figure 2–2, had to be added since the venturi fuel feed system of the valved jet was removed to put on a valveless inlet.

![Figure 2–2: Dimensions of Experimental Jet](image-url)
The thermal load was too much for the aluminum heads, resulting in the melting of the threads and run time was severely limited to avoid this problem, so three of the working inlets were re-made, this time out of steel. After many runs, the jet started to deform due to thermal stresses, two replacement jets were purchased. One of them had just a fuel injection port welded on to it, while the other had a fuel injection port as well as eight ports added for measurements. The new ports were placed in pairs, offset by 90° at the four axial locations that are shown in Figure 2–2. Note that there is no port 2. This was due to similar data at ports 1 and 2 along with the determination that the original port 1 was in a recirculation zone since as a whole, all the pressures were lower. The first pair of ports was placed in the middle of the original ports 1 and 2, directly downstream of the fuel injector, while the last 3 axial locations remained in the same locations. A computational flow visualization also showed a recirculation zone right behind the valve face, where port 1 is located.

2.2 Cooling System

A new cooling system was designed for these ports because of the loss of a thermocouple on a 15 centimeter class pulsejet due to heat exposure. Instead of copper tubing, water jackets were made to protect the thermocouple, seen in Figure 2–3. These water jackets provided much better heat transfer since the water was in actual contact with the port, instead of having a layer of copper in between. At the front of the jet, port 1, it was necessary to use the old method of copper tubing wrapped around the port. Due to the proximity of the fuel injector port, there was insufficient room for the copper water jacket, so tubing was used, this time twice as much.
2.3 Inlets

A second set of inlets were made with a fixed diameter of ½” but lengths varying between 1 and 3 inches in 1 inch increments. After some experimentation a fourth inlet was made out of steel, with adjustable lengths. This ½” inlet was made with 3 pieces so that the length could be set at 1”, 2”, and 3”. The inlet selection can be seen below in Figure 2–4.
2.4 Fuel Delivery

Fuel was fed into the system, via a precision needle valve and flow rate was measured with a 0-30 SLPM (air) Hastings Flow Meter and Hastings Instruments Model 40 flow meter (Figure 2–5). This meter was able to measure flow rates up to 25.5 SLPM of Propane with an accuracy of +/- 0.1 SLPM. This affected the measurement of the upper throttleability limits of the 7/8” and 1” inlets because they were able to run at higher flow rates that could not be accurately measured with the flow meter.

The selected fuel injector was picked from a group of three injectors. The most reliable one was chosen based on the ability to start the jet run after run. The other injectors performed better at certain conditions, but the selected injector had the best overall performance. The chosen injector, shown in Figure 2–6, was made of 1/8” stainless steel and spanned the entire jet combustion chamber. Twenty 1/16” holes were drilled through parallel to one another and 180° offset.
2.5 Ignition System

The jet was started using a miniature spark plug to provide the necessary temperatures to start the combustion process. A nichrome wire ignition system was initially tested, but abandoned in favor of the spark ignition system. Both systems can be seen installed in jets below in Figure 2-7. A nichrome wire was passed through a 1/8” piece of ceramic with 2 conduits. The 2 pieces were joined inside the jet with a heavier gauge nichrome wire. The other ends of the wire were connected to a rheostat. High temperature RTV was used to seal the gap between the ceramic shroud and steel jet. Starting the jet was successful, but the cooling by convection of air passing over it in the starting process made
starting more difficult and time consuming since the wires heat up slower than the plasma created by a spark ignition system. The wires would also have a tendency to burn up over extended use.

Figure 2–7: Nichrome Ignition (top) and Spark Ignition (bottom)

2.6 Pressure Measurements

Both time-average and instantaneous pressures were measured at various axial locations in the jets. The instantaneous pressure provided both the operating frequency and the peak-to-peak fluctuations. To measure average pressure, the mercury manometer shown in Figure 2–8, was used and placed on the side ports of the jet via extension hose. A mercury manometer was chosen due to the inertia of fluid’s ability to absorb high frequency oscillations. With the oscillations removed, an average pressure could be measured. This is an analog way of averaging the digital data over time.
For instantaneous pressure, a Kulite XTE-190-5G pressure transducer was used and connected to a 12-V battery. A battery was required because the initially used AC to DC inverter created too much noise in the data and was replaced. This pressure transducer was connected to an HP54503A Oscilloscope. Data was then transferred to a P2 400MHz computer via a National Instruments GPIB Card. This allowed for data to be put in to a
spreadsheet for analysis. The data was then shifted by an offset so that the average pressure of a cycle equaled the average pressure measured by the manometer.

2.7 Thermocouples

Type-B thermocouples were used. These thermocouples were custom made, using a junction of two slightly different types of metal, in this case platinum and platinum/rhodium. Type-B thermocouples were chosen due to their high temperature capability, reliability, and ability to withstand the harsh environment of the jet. The junction of two dissimilar metals produces a temperature dependent voltage. The wires were passed through ceramic material due to its ability to withstand high temperatures. A 1/4" cap was drilled out and the ceramic was epoxied so that when installed, the thermocouple would be in the centerline of the jet. An example is shown below in Figure 2–9. The voltage was measured with a Pentium 4 computer via a data acquisition card with a maximum input of 4 Hz per channel. Three thermocouples were used to test the jet's temperature at various locations along the jet. The various lengths were chosen to get the probe in the centerline of the jet.

![Completed Type-B Thermocouple](image)

**Figure 2–9: Completed Type-B Thermocouple**

Laboratory ambient temperature was measured using a simple thermometer shown in Figure 2–10.
This temperature was used to correct pressure data to Standard Day conditions.

2.8 Sound Pressure Level Meter

To measure sound, a Radio Shack Sound Level Meter was used, seen in Figure 2-11, accurate to the nearest decibel. The meter was placed facing the exhaust, 4 feet away, at a 30° offset. 30° was chosen because of acoustic standards; sound out of a tube is loudest at 30° off of the centerline.
2.9 Thrust Stand

The pulsejet was secured to a low-friction linear bearing assembly made by Tusk with a custom aluminum plate. Aluminum mounting brackets held the jet to the plate and the jet was secured to them using steel bands. A linear potentiometer was connected to a steel plate that was secured to the linear bearing assembly. The other side was connected to the table via an anchor point. Power was supplied to the potentiometer by a DC Power Supply set to 10 V. Distance versus voltage was then calculated to be 0.4 in/V. A spring with a spring constant of 1.1 lb/in was used to obtain the force applied. After several failed attempts, it was decided that thrust could not be measured using the geometry we were testing since it has two opposing exhaust pipes and the thrust was too small to discern. Various inlets were tried with the same result. It should be noted that when fed air, the jet would pull itself toward the air source.

2.10 Procedures

2.10.1 Starting of the Jet

Starting the pulsejet began with two things, the need to supply the first intake of air and a way to ignite the mix of fuel and air. The valved pulsejet had a fuel delivery system based off of venturi tubes which utilize Bernoulli’s principle which states that as air velocity increases, static pressure decreases. This decrease in static pressure caused by the incoming air pulled fuel through holes tangential to the surface. These small holes created a fine mist of droplets that entered the combustion chamber, vaporized and mixed with air after passing over the valves. In the valveless configuration, the fuel used was gaseous propane and was directly injected in to the combustion chamber behind the inlet. After the mixture entered the chamber, it was ignited by a spark. After the initial combustion events occur, the engine
continued to run on its own. A warm jet was found to be easier to start than a cold jet; this is most likely due to the effect of heat transfer at the walls. After the jet is running, the ignition can be turned off and the forced air can be stopped. To stop both the valved and valveless jets, the fuel supply was simply cut off using a valve.

2.10.2 Data Collection

Data collection was performed using various input devices, some by eye, some by hand, others by machine. Care was made when calibrating the high speed pressure transducer. Every day a baseline case was run prior to the test runs. The baseline case was compared to the atmospheric conditions and used to correct the data.

Initial ethanol pressure measurements were collected by an Agilent Infinium Oscilloscope 500 MHz 2 Gigasamples per second. For later experiments a different oscilloscope was used. The latter one was a bit older and required a computer to acquire the data from the oscilloscope.

A LabView code was written to talk to the HP54503A oscilloscope and transfer the data off of it. This code collected 500 points of data from each oscilloscope trace, or about 100 points per cycle. The Kulite transducer was chosen for its ability to withstand a high temperature while taking high frequency pressure measurements; however its noise level was higher than the Omega DPX101-250 transducer that was used in for the valved jet with a +/- 2 psi error range. This is why the data had to be corrected using a manometer.

Thermocouples were readily checked for problems and tested to insure they were in good working order. Thermocouples, pressure transducers, manometers, and fuel lines were attached or inserted to the 1/4” diameter ports along the jet. Standard compression fittings were used to ensure a tight seal and no leakage.
3. **Parametrics / Performance**

3.1 **BMS Valved Tests**

Various measurements were taken at different lengths to gather a general understanding of how the jet operates as well as give a baseline for any comparisons to the valveless variant. To understand the cycle times of the BMS pulsejet, a HeNe laser was used to illuminate the valve pedals from the front, and a high speed camera was used to take images at 2000 Hz. The illumination was needed due to the cameras speed and light sensitivity. Since the jet operates at around 230 Hz, roughly nine frames per cycle were obtained. When observed, the valves were open during 33% of the cycle. This means that the intake of air is happening only 1/3 of the cycle.

In order to gauge the volume and temporal extent of the actual combustion process, CH* measurements were taken. CH* is an intermediate radical that is only present during combustion and can be detected by looking at the 433 nm band of the electromagnetic spectrum. A photomultiplier tube was connected to a fiberoptic cable that was then connected to each of the ports added to the jet. If CH* was present, combustion was occurring. It was determined that CH* was detectable up to the converging section of the jet. After that section, no CH* emission was observed.

CH* was compared to the combustion chamber pressure and is shown below in Figure 3–1. It shows that combustion is occurring during about 45% of the cycle.
Fuel consumption for the valved jet was determined by weighing the fuel as the jet was running. Data was taken every 30 seconds and was used to compute the average fuel consumption. This was tested at various lengths. The lowest consumption occurred with a six inch extension added to the jet, 2.4 g/s. This is compared to the stock length fuel consumption of 2.5 g/s, and the nine inch extension fuel consumption of 2.6 g/s.

Pressure measurements were taken at two ports along the jet and can be seen in Figure 3–2. The pressures at ports 1 and 2 were very similar both in shape and in peak pressure with port 2 being slightly lower. On later jets, they were consolidated in to one port that was located half way between them.
Temperature measurements were also taken and can be seen in Figure 3–3. This figure shows the starting process of the jet as well as part of the cool down phase.
The highest temperature is reached in the converging section immediately following the combustion chamber.

3.2 Valveless Tests

Measurements similar to that of the valved jet were taken, not only at various lengths, but various inlet diameters as well. The overall test data can be seen in Table 3–1.
Table 3–1: Overall Test Results

<table>
<thead>
<tr>
<th>Inlet Length (in.)</th>
<th>3</th>
<th>3</th>
<th>2</th>
<th>3</th>
<th>3</th>
<th>3</th>
<th>32</th>
<th>3</th>
<th>3</th>
<th>3</th>
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<tr>
<td>Diameter (in.)</td>
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<td>0.875</td>
<td>0.5</td>
<td>0.5</td>
<td>0.625</td>
<td>0.875</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.625</td>
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<td>1</td>
</tr>
<tr>
<td>Exhaust Extension Length (in.)</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Throttleability (SLPM Propane)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Flow Rate</td>
<td>19.5</td>
<td>18.7</td>
<td>10</td>
<td>10</td>
<td>22.5</td>
<td>&gt;25.5</td>
<td>&gt;25.5</td>
<td>12.5</td>
<td>12</td>
<td>22.7</td>
<td>25.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Low Flow Rate</td>
<td>8</td>
<td>11.5</td>
<td>7</td>
<td>7</td>
<td>6.5</td>
<td>10.6</td>
<td>15.5</td>
<td>4.2</td>
<td>3.9</td>
<td>5.5</td>
<td>11.7</td>
<td>16</td>
</tr>
<tr>
<td>Range</td>
<td>11.5</td>
<td>7.2</td>
<td>3</td>
<td>3</td>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
<td>8.3</td>
<td>8.1</td>
<td>17.2</td>
<td>13.8</td>
<td>9.5</td>
</tr>
<tr>
<td>% of Max</td>
<td>0.41</td>
<td>0.61</td>
<td>0.70</td>
<td>0.70</td>
<td>0.29</td>
<td>N/A</td>
<td>N/A</td>
<td>0.34</td>
<td>0.33</td>
<td>0.24</td>
<td>0.46</td>
<td>0.63</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High SPL (dB)</td>
<td>114</td>
<td>118</td>
<td>108</td>
<td>112</td>
<td>110</td>
<td>120</td>
<td>121</td>
<td>107</td>
<td>110</td>
<td>116</td>
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<td>120</td>
</tr>
<tr>
<td>Low SPL (dB)</td>
<td>111</td>
<td>115</td>
<td>108</td>
<td>107</td>
<td>105</td>
<td>109</td>
<td>116</td>
<td>102</td>
<td>105</td>
<td>105</td>
<td>113</td>
<td>115</td>
</tr>
<tr>
<td>Test Fuel Flow Rate (SLPM)</td>
<td>14.8</td>
<td>14.8</td>
<td>10</td>
<td>10</td>
<td>14.8</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>14.8</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Operating Frequency (Hz)</td>
<td>220</td>
<td>253</td>
<td>200</td>
<td>183</td>
<td>214</td>
<td>244</td>
<td>259</td>
<td>198</td>
<td>178</td>
<td>196</td>
<td>223</td>
<td>246</td>
</tr>
<tr>
<td>SPL (dB)</td>
<td>114</td>
<td>117</td>
<td>108</td>
<td>112</td>
<td>108</td>
<td>118</td>
<td>118</td>
<td>107</td>
<td>110</td>
<td>111</td>
<td>117</td>
<td>118</td>
</tr>
</tbody>
</table>
For each inlet a fuel flow was chosen based on throttle range as well as the ability to compare to other inlets / data analysis. For instance the flow rate for the 1/2” inlet was 10 standard liters per minute (SLPM). This flow rate was chosen due to the ability of the jet to run at all working inlet lengths, the 2 and the 3 inch, as well as a series of extension lengths. The 5/8” jet was run at 14.8 SLPM to match with computational data. The 7/8” and 1” inlets were both run at 20SLPM, except for the 3” exhaust condition where the 1” would not run at any flow rate and the 7/8” would not run at any rate below 18.7 SLPM. In that case, it was run at 14.8 SLPM to compare to the 5/8” inlet.

Since the flow meter will not measure past 25.5 SLPM, which is the recorded data for any condition that reaches it. Those numbers should be taken to read “at least 25.5 SLPM”. This affected how the throttleability range is depicted. Decibel measurements were taken 4 feet away at a 30° offset and recorded at the highest and lowest throttleability limits with the intent of correlating these measurements with pressure and indirectly with thrust.

Long term cycle histories were used to determine the average operating frequency over an average of 40 cycles. Short term cycle histories were recorded initially at 5 ports. It was determined that ports 1 and 2 yielded similar results so they were consolidated in to one port, a new port 1, in which its location was in the middle of the two ports when the second jet was made. The second jet had four ports, and does not have a port 2 due to the consolidation of the ports mentioned earlier.

Temperatures were recorded at three locations along the centerline for each case. The inlet temperature was taken by using a thermocouple held directly in front of the inlet, the second was placed after the converging section of the combustion chamber. In some instances, the thermocouple in the combustion chamber did not register any temperature,
though it was glowing red. It was analyzed and swapped out with a known working
thermocouple and the same results were obtained. In instances where there were no
combustion chamber readings, they are left off of the figures. The final temperature port was
the exhaust exit. The thermocouple was placed ½” in to the exhaust stream, before the flare.

![Figure 3-4: Lower Throttletability Limit for Various Extension Lengths](image)
Comparing the fuel flow rate to the inlet diameter, shown in Figure 3–4 and Figure 3–5, it shows that as the inlet diameter is increased, more fuel is required to run the jet. This is due to the amount of air that is ingested in each cycle. Adding various extensions shows the same trend, which is an increase in fuel required. Longer extensions allow a wider variety of inlets to operate and allow lower fuel flow rates to be obtained.

When compared with extension length, the required fuel flow rate is also affected, though not as drastically as it is affected with changes in the inlet diameter. Inlet length is compared here as well for the ½” Inlet. It was run at 2 and 3 inches in length using 6” and 9” extensions. The trends are similar with the shorter inlet having a slightly higher, lower limit. As the inlets increase in diameter, the slope of their lines turns from negative to positive. The 7/8” inlet seems to have a minimum of 10.3 SLPM at 6” exhaust extension length.
Figure 3-6: Upper Throttleability for Various Extension Lengths

Figure 3-7: Upper Throttleability for Various Inlet Diameters
Figures 3–6 and 3–7 show that the limits of the flow meter are 25.5 SLPM propane. Inlets that reach those values should be read as “at least that amount”. Each inlet appears to plateau at some point, but that could not be tested with the current setup. A larger mass flow meter would be needed in order to obtain accurate readings. Inlet diameter has a much greater effect on the upper limit of the flow rate than the inlet length does. This makes sense due to a larger inlets ability to ingest more air per cycle due to a larger circumference and cross-sectional area.

At shorter exhaust lengths, only two inlets could be successfully started, as the exhaust length increased, more inlets were able to be started. The larger inlets tend to have a larger fall off in the upper limit at shorter lengths. Inlet length has a small effect on the upper throttleability range with the 2” performing just slightly better than the 3” at longer exhaust lengths.

![Figure 3-8: Temperature vs. Exhaust Length for ½” Inlet (3” Long)](image)
As shown in Figures 3–8 and 3–9, temperature distributions for both 2 and 3 inch $\frac{1}{2}$” diameter inlets show the same trends. The inlet temperatures in these cases are hotter than the exhaust. This is contrary to the expected results. Usually, the exhaust temperature is higher than the inlet temperature. At the lower inlet sizes, a lower fuel flow rate is used, this means less air in ingested. The inlets exit is closer to the combustion chamber than the exhaust exit. Also to note that as extension length grows combustion temperature goes down. The exhaust temperature is level.
Figure 3-10: Temperature vs. Exhaust Length for 5/8" Inlet

Figure 3-11: Temperature vs. Exhaust for 7/8" Inlet
The 5/8” has the same trends except the exhaust temperature is getting closer to the inlet temperature as shown in Figure 3–10. The inlet and exhaust temperatures are unaffected by length. The larger inlets are cooler than the exhaust and this seems to be due to the large amounts of air that are ingested at higher fuel flow rates. The exhaust temperature seems to reach a maximum at 6” in length as can be seen in Figure 3–11.

Figure 3–12: Temperature vs. Exhaust Length for 1” Inlet

At 1”, Figure 3–12, the exhaust temperature is much higher than the inlet temperature and it increases with increasing length. Extensions for a long enough jet were not available to test these trends fully. It is important to note that in Figures 3–1 and 3–12 the combustion chamber pressure was not measured. This is due to some anomaly with the flow field in that location. Different thermocouples were placed in the same location with the same results.
Figure 3-13: Jet Temperatures vs. Inlet Diameter +3” Extension, 3” Long Inlet

Figure 3-14: Jet Temperatures vs. Inlet Diameter +6” Extension, 3” Long Inlet
As shown above in Figure 3−13, Figure 3−14, and Figure 3−15, inlet temperature reaches a maximum at an inlet diameter of 5/8” and occurs with different extension lengths with the same patterns. The only differences are that the inlets that the jet is able to operate with and an increasing fuel flow rate as the inlet diameter increases. The combustion chamber temperature drops with increasing length for a given inlet even as the fuel flow rate is increasing. I believe this is due to the increase in the amount of incoming air required for combustion.
Figure 3–16 shows that inlet length makes little difference with respect to throttleability in the case of the ½” inlet, the lines lie on top of one another. The 5/8” inlet starts off with higher throttleability which continues to increase but at a decreasing rate. The measurements for the 7/8” and 1” inlets’ throttleability values for extension lengths longer than 6 inches mean ‘at least that value’, and are only decreasing due to the lower limit increasing and the upper remaining at 25.5 SLPM. The flow meter reached its limit at 25.5 SLPM.
Figure 3–17: Operational Envelope based on Inlet and Exhaust Length

Figure 3–18: Throttleability Ranges for Various Extension Lengths with Various Inlets
In Figure 3–17, the pairs of lines above in each figure represent the upper and lower limits for each configuration. In Figure 3–18, the ½” Inlet was run with 2 different lengths, the standard of 3” and on 2 occasions, 2” length. They are denoted in the legend as (2). It also suggests an initial rise in upper limit with added exhaust length followed by a level period. Smaller inlets start at longer lengths, as do larger inlets.

Shorter exhaust lengths have tighter envelops, larger inlet diameters are not depicted correctly due to the limit of the flow meter, but the trend is still seen to be the same as with the others.

![Operating Frequency as a Function of Exhaust Length for Various Inlets](image)

**Figure 3–19: Operating Frequency as a Function of Exhaust Length for Various Inlets**

As expected, Figure 3–19 shows that the frequency decreases as exhaust length is increased. This happens in all cases. As the inlets diameter decreases, so does the frequency, this also expected. This suggests that both play a role in the operational frequency of the jet.
The inlet diameter to frequency again shown in Figure 3–20, show a strong relation to inlet diameter. Length is shown to have a less dramatic effect. Pressure was also measured from three ports, ports 1, 3, and 5. Data from port 4 was not taken since it was of little value, other than comparing with computational work at the inception of the project. Ports 1 and 3 are similar, but have slight differences due to a growing effective combustion chamber.
Figure 3–21: Change in Port 1 Pressure vs. Inlet Diameter

Figure 3–21 shows the change in port 1 pressure as a function of inlet diameter. Each line is for a different extension length. The trend shows that as inlet diameter is increased, the change in pressure reaches a maximum. The 3” extension would only allow half of the inlets to operate, the 6” shows a decline in ΔP between the largest inlets. For the 9” extension the decline from 7/8” to 1” inlet is negligible. The longer the inlet, the more stable the jet, its ΔP is less sensitive to inlet diameter changes. As jet length decreases, the slopes in the curves get steeper and the operability range of the jet is affected at the low end by the ability to make enough pressure.
The average pressure, shown in figures Figure 3–22 and Figure 3–23, was compared to all 3” inlet configurations. When compared to diameter, the average pressure reaches a maximum for all cases with the 5/8” inlet. As the jet length is increased, the average pressure decreases. Port 3 on the 6” and 9” extension jets starts off with the 6” jet having a higher average pressure when used with the 1/2” inlet, after that, coming together and following the same trend as diameter increases.
When compared with length, the difference between port 1 and port 3 increases as length is added, the exception is the ½” inlet. It does not reach a plateau in its operational range. All other inlets show a plateau for port 3 pressures with increased exhaust length. This is good to know when designing a jet; it shows that for a given diameter as length is increased, chamber pressure will increase up until a certain length, after which it plateaus.

Comparing the inlet frequency versus the frequency at the exit of the jet shows that the third harmonic is visible. Shown in Figure 3–24, the inlet is operating at 255Hz, while the exit is calculated to be operating at 765Hz. This is more prevalent in larger inlets, however smaller ones do exhibit the same features, Figure 3–25.
Figure 3–24: 2nd Harmonic Visible in Exhaust Frequency for 1" Inlet

Figure 3–25: 2nd Harmonic Visible in Exhaust Frequency for 1/2" Inlet
The prevalence in larger inlets is due to a higher fuel flow rate which leads to a higher sound pressure level. Harmonics are amplified more with higher SPL’s. This is expected because as sound pressure levels are increased, it increases the amplification of harmonics. This data was taken using the Kulite pressure transducer, the data has a lot more noise than the DPX-101 pressure transducer, however it yields more consistent results.
4. Helmholtz Resonators and Quarter Wave Tubes

4.1 Helmholtz Resonators

A Helmholtz resonator is a container of gas with an open hole or neck. A volume of air in and near the open hole vibrates because of the 'springiness' of the air inside. This applies to containers in which the wavelength of sound is much longer than the dimensions of the container. The following equation shows that the frequency, \( f \), is inversely proportional to the square root of the tube length since \( c \), the speed of sound, \( V \), the volume and \( S \), the area, are constant.

\[
f = \frac{c}{2\pi} \sqrt{\frac{S}{VL}}
\]

The Helmholtz resonator model was chosen due to the similarities with the inlet of the jet. The valveless pulsejet’s inlet acts like a resonator since it shares the same combustion chamber as the exhaust, the combustion chamber acts like a spring or compliance. Since the volume of the combustion chamber is much larger than the volume of the inlet, it is a safe assumption.

4.2 Quarter-wave Tubes

A quarter wave tube is defined as a tube with one end sealed off and one end open. It is similar to a Helmholtz resonator, but different in that it has no cavity behind it. The equation for its frequency is

\[
f_r = \frac{c}{4L_0}
\]

The actual pulsejet has a combustion chamber attached to the exhaust so this compliance alters the equation. After conducting tests with the valved jet, it acted like a
mixture between the two resonant cavities. It acts closer to a ‘1/6’ wave tube due to valves opening and closing in each cycle. A quarter wave tube does a good job at describing the exhaust, in general, since the changes in frequency mimic that of how the exhaust operates. The valveless inlet is simulated as a Helmholtz resonator due to its size and relatively small impact on overall frequency. Neither the ½ nor the ¼ wave model simulate the operation of the pulsejet due to area changes. Area changes cause reflections of the wave and this is what determines the frequency of the jet. The 1/6 wave does model the operational frequency very well at this scale.

Since both of these equations depend on the speed of sound, they are temperature dependant. Figures 4–1 and 4–2, actual versus modeled frequencies for 5/8” and 7/8” inlets, show the calculated Helmholtz and 1/6 wave tube frequencies compared to the actual operating frequency of the jet. The Helmholtz frequency, shown with squares, increases with increasing exhaust length and then remains steady after 6” has been added. This is mostly due to the temperature changes and the effects on the speed of sound. The 1/6 wave tube frequency, shown with diamonds, decreases as length is added, this is expected. The actual operating frequency lies in the middle of those two lines and is shown as triangles.
Figure 4-1: Actual vs. Modeled Frequencies for 5/8" Inlet

Figure 4-2: Actual vs. Modeled Frequencies for 7/8" Inlet
For the 5/8” Inlet there is a point of intersection at the 6” Exhaust Length. That location is where the model is predicting that both the inlet and exhaust frequencies match and they match with the measured frequency as well.

When compared to different lengths, the inlets effect is shown below in Figure’s 4−3, 4−4, 4−5, and 4−6. All Inlets show a similar trend where the theoretical Helmholtz frequency is increasing as length is added and the theoretical 1/6 wave frequency is decreasing as length is added. For the smaller inlets there is a point at which they are equal. For the 1” inlet, they have already passed that point and are growing further from one another. The average frequency still predicts the jet frequency however.

![Figure 4-3: Actual vs. Modeled Frequencies for 1” Inlet](image)
Figure 4–4: Actual vs. Modeled Frequencies as a function of Inlet Diameter for 3" Exhaust

Figure 4–5: Actual vs. Modeled Frequencies as a function of Inlet Diameter for 6" Exhaust
The Predicted and Actual Frequencies are compared below in Table 3–1. The top row lists, in order, the inlet diameter followed by the inlet length, followed by the exhaust extension length, all in inches. The average frequency of the Helmholtz and 1/6 wave tube are compared to the measured frequency. The largest error is 5%, for the 5/8” inlet with 3” Extension. All other predicted frequencies are below 4%. Accurate temperature measurements are critical in the calculations since both the Helmholtz and 1/6 wave tube models are based off of the speed or sound which is proportional to $T^{1/2}$. 

![Graph showing Actual vs. Modeled Frequencies as a function of Inlet Diameter for 9” Exhaust](image-url)
Table 4-1: Actual Frequency Compared to Calculated

<table>
<thead>
<tr>
<th></th>
<th>5/8 3 3</th>
<th>7/8 3 3</th>
<th>1/2 2 6</th>
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<th>5/8 3 6</th>
<th>7/8 3 6</th>
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<td>Inlet frequency Hz</td>
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<tr>
<td>Exhaust frequency Hz</td>
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<td>258</td>
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<td>212</td>
<td>214</td>
<td>211</td>
<td>216</td>
<td>187</td>
<td>181</td>
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<td>202</td>
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<td>169</td>
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<td>249</td>
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<td>0.95</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
</tbody>
</table>
5. **Sound Pressure Levels**

Sound Pressure Levels were measured using a Radio Shack SPL Meter. They were measured at each length and with each inlet. Below in Figures 5–1 and 5–2, the 6” extension is quietest overall and reaches a minimum with the 5/8” Inlet. This also happens to be the point at which the Helmholtz frequency equals the 1/6 wave frequency.

![Figure 5-1: SPL vs. Inlet Diameter for Various Lengths](image)
Figure 5-2: SPL vs. Extension Length for Various Inlets
6. Conclusion

The effects of lengthening the exhaust tube length on frequency are similar on both valved and valveless jets. The valveless jet is less sensitive to changes in length than the valved jet is, this is due to the fact that a valveless jet head behaves more like a Helmholtz resonator and thus speeds the jet up. It is also noted that the valved jet operates closer to $\frac{1}{4}$ wave tube than the valveless. By increasing the exhaust length, the throttleability increases as well. A maximum can be reached for certain inlets in the valveless configuration. Upper throttleability limits plateau at specific exhaust lengths while the lower throttleability limit continues to decrease.

The effect of changing the diameter of the inlet is that the frequency increases with increasing diameter. The change is linear and thus it can be modeled as a Helmholtz Resonator. The temperature effect of increasing inlet diameter is that the exhaust temperature rises (due to it being fuel rich) and the inlet temperature decreases (due to increased air intake).

The current configuration produces little thrust due to the experimental setup that includes opposing inlet / exits. The exhaust exit geometry is sensitive to shape. A flared tip is preferred and sometimes required for operation. The 50 centimeter class pulsejet can be modeled as the average of the inlet's Helmholtz frequency and the exhaust’s $1/6$ wave tube frequency.

Highest average combustion pressure occurs with $5/8''$ inlet, this is due to the flow not fully expanding at high fuel flow rates and combustion occurring in exhaust tube. Combustion chamber peak pressures are significantly higher for valved jets.
7. **Future Work**

Investigating this phenomenon at different scale sizes is important and should be verified. The combustion chamber volume should have a sleeve inserted in to it to reduce the volume and see how it affects the operating frequency. A CH* test should be performed to check for combustion at the ports downstream of combustion chamber for higher fuel flow rates. Skin temperatures should be measured axially along the jet to help model the jet computationally. A U-tube or rearward facing inlet should be used to create measurable thrust and calculate thrust specific fuel consumption.
References


9. Piot, Désiré Thomas, 1898, “Improvements in Steam Generators applicable for Propelling Boats”, GB189726823


