Abstract

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An experimental 8 cm pulsejet was developed using scaling laws from research on both 50 and 15 cm pulsejets. The 8 cm jet operates in three different inlet configurations—conventional, perpendicular, and rearward. The rearward configuration features inlets facing in the opposite direction of the flight path and develops the maximum net thrust. Using a high frequency pressure transducer, the operational frequency of the pulsejet was obtained by monitoring the combustion chamber pressure. It was found that in the rearward configuration, the operational frequency of the jet decreases with increasing inlet length. In addition, the combustion chamber peak pressure rise per cycle increases significantly if the exhaust diameter is reduced. Using information from the 8 cm pulsejet, a 4.5 cm pulsejet was developed and is operational.

EXPERIMENTAL INVESTIGATIONS OF MINI-PULSEJET ENGINES

by

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Biography

The author was born Adam Paul Kiker on April 8, 1981 in Raleigh, North Carolina, to Paul and Gail Kiker. He has an older brother, Jason, and a younger half-brother, Austin. He grew up in Raleigh, but graduated Valedictorian of Anson High School in Wadesboro, North Carolina. For many reasons, including the fact that his father is an alum, Adam attended North Carolina State University where he played five years of college football—earning a varsity letter three of the five years. Upon graduating in May 2003, Adam decided to prolong his college career and pursue a Master of Science in aerospace engineering, largely in part because he had one more season of football to play. Once his masters degree is completed, Adam will take a job with Hobbs, Upchurch, and Associates where he will enter as a project engineer.

Acknowledgements

The author would like to acknowledge his advisor, Dr. William Roberts, whose never-ending appreciation for academia and the advancement of his students deserves far more recognition than he could ever receive; Dr. Andre Kuznetsov, Dr. Taofang Zeng, Dr. Terry Scharton, Tiffany Berry, Sean Danby and Peter Nyahoro for their advise and assistance; and Rufus "Skip" Richardson and Mike L. Breedlove for their strong commitment to this project—without their prompt help many deadlines would have been missed.

The author would also like to thank his parents, Paul Kiker and Gail Kiker, and his step parents, Dr. William Strickland and BJ Kiker, whose constant love and support in all of his endeavors made it impossible to fail. Contrary to the beliefs of many, having four caring parents has been a true blessing. Lastly, the author would like to thank his two brothers, Jason and Austin, for their love, leadership, and friendship.

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1 Introduction

1.1 Origination of the Aeropulse

The concept of a jet engine was developed in the early twentieth century when engineers began to realize certain disadvantages to rocket power plants. Unlike jet engines, rockets carry their oxidizer with them in flight. Engineers began to consider using oxygen from the atmosphere as their oxidizer, hence eliminating the need for an extra oxidizer tank.

The key to producing propulsive thrust is the ability to convert chemical enthalpy into kinetic energy by expanding a combustion product from a pressure much higher than atmospheric pressure down to atmospheric pressure (Tsien 404). In other words, combustion needs to happen at high pressure. Engineers realized two ways to accomplish this goal. The first being to convert the relatively high speed air in comparison to a fast moving vehicle into pressure energy through a diffuser—hence a ramjet.

The second concept was to carry out combustion at constant volume. Air is sucked into a combustion chamber, the chamber is sealed off, and fuel is added, mixes, and is burned. This creates a combustion chamber pressure much higher than atmospheric. The high pressure fluid is then allowed to expand through an exhaust tube, and the process starts over. The operation and trust are both cyclic—hence an aeropulse.

The first application of the aeropulse came during World War II on the German V-1 flying bomb. At nearly twelve feet in length with a combustion chamber diameter of roughly two feet, the V-1 operated at a very low frequency—roughly 50Hz—and was deemed the “Buzzbomb.” The process began with air being sucked into the combustion chamber by the vacuum created from the previous combustion cycle. The air then passed through an inlet venturi where gasoline was continuously injected. Once inside the combustion chamber, the fuel and air mixed and burned. The high pressure generated from the combustion event closed the spring valve covering the face of the inlet. The mixture was forced to expand through a long exhaust tube, hence creating the propulsive impulse. The velocity of the exhaust gas created a vacuum in the combustion chamber which opened the inlet valves and allowed the process to start over (Tsien 405). On the whole, this cyclic process can be used to describe most all valved pulsejets.

1.2 Valveless Pulsejet Design

The aeropulse is a very simple device that is characterized by its lack of actively moving parts. For the valved pulsejet, the only component that moves at all is the set of reed valves covering the combustion chamber inlet. Although simple when compared to the modern turbojet, the functionality of the reed valves provides the only serious chance for mechanical failure. This led engineers to develop a valveless model for the aeropulse.

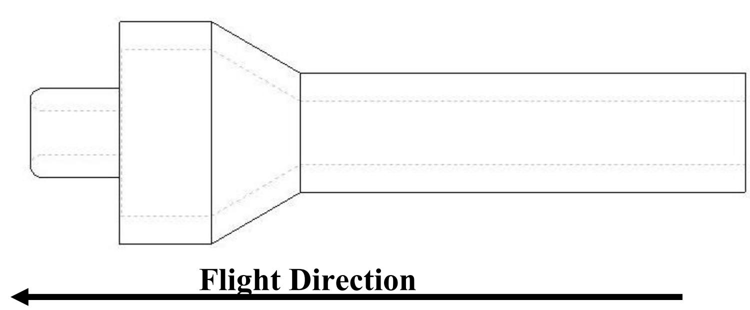

Figure 1: Valveless Pulsejet Design Sketch

The valveless design, shown in Figure 1, is characterized by its total lack of moving parts—the engine's geometry alone controls the operation of the jet. Replacing the valves of the conventional pulsejet and serving as the jet's inlet is an air diode. Because the inside diameter of the air diode is less than that of the exhaust, combustion chamber pressure is allowed to build sufficiently enough to force most of the combustion products out the exit of the jet. However, when compared to the valved model, there is a much larger amount of gas expelled out the inlet during each cycle. This negative velocity gas reduces the valveless pulsejet's net thrust significantly relative to the valved engine.

1.3 Various Inlet Configurations

In the conventional valveless inlet configuration, the inlet faces forward and the exhaust faces rearward. As one would expect, this results in the combustion chamber products being expelled in both the forward and rearward directions. This expelling of products in both directions cuts down on any net thrust produced by the pulsejet—for every slug of product pushed out the exhaust producing positive thrust, there is a coinciding slug of fuel being expelled out the front producing negative thrust. For the valved pulsejet, the reed valves prevent any product from going out the inlet and force everything out the exhaust.

In order to turn this negative thrust into a more productive phenomenon, the inlet direction was turned to perpendicular to the flight direction, as shown in Figure 2. In the perpendicular configuration, the products expelled out the inlet have a neutral effect on the pulsejet's thrust, increasing the jet's overall net thrust.

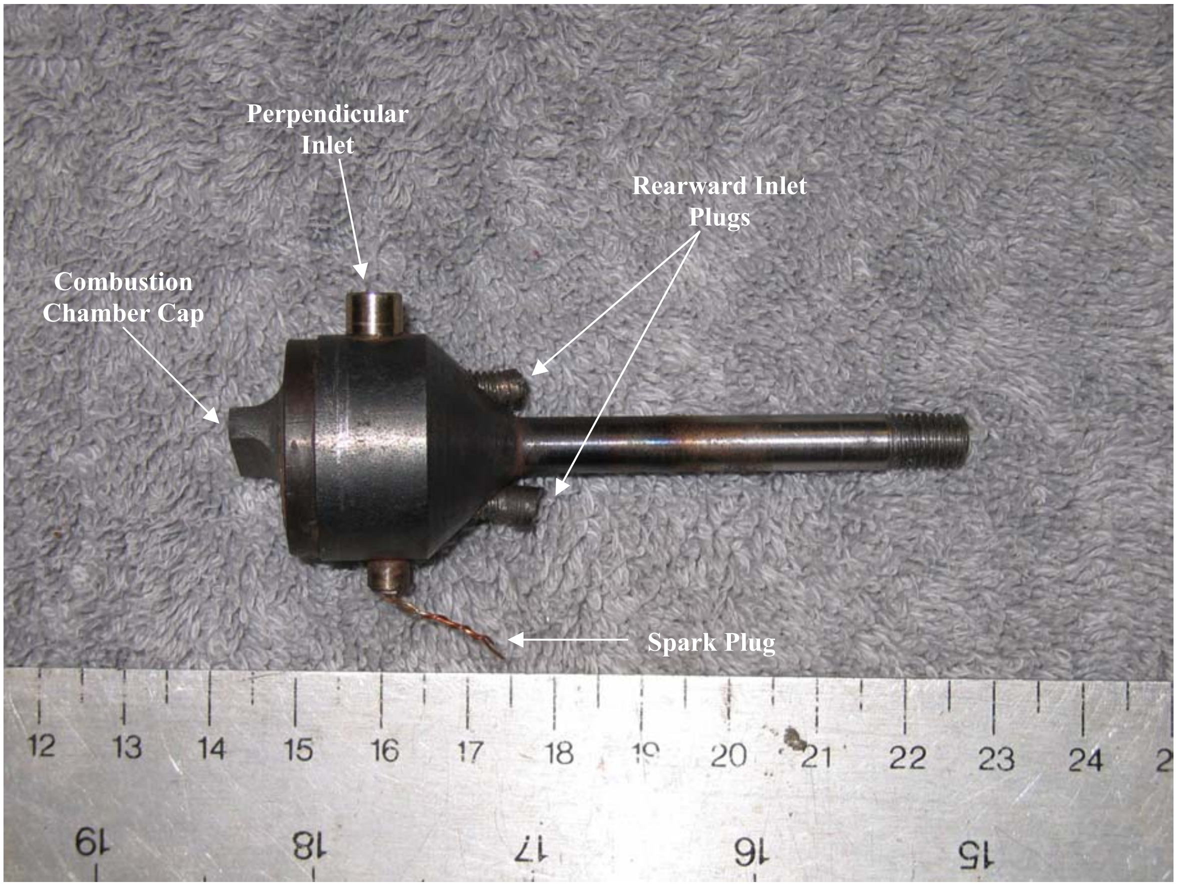

Figure 2: Pulsejet in Perpendicular Inlet Configuration

Finally, in an attempt to create positive thrust out of the inlets, the rearward inlet configuration was developed in which two different inlets face the opposite direction of the flight path. In this configuration, any products expelled out of the inlets add to the pulsejet's thrust rather than taking away from it. The rearward configuration enables the valveless pulsejet to maximize its net thrust

1.4 The Pulsejet as a Miniature Propulsion Device

The object of this research was to develop a functional pulsejet with an overall length of 2 cm. The 8 cm jet was simply a stepping stone in the shrinking process. The pulsejet was chosen because of its simplicity. When developing micro-propulsion devices, it is assumed that having a minimum of moving parts makes many facets of the engineering process much easier. However, when attempting to operate a device roughly the size of your pinky, many fundamental problems can arise.

The first of which is the dilemma with manufacturing an engine so small. Although 8 cm is not small relative to modern, high precision machining techniques, these techniques were not readily available. In addition, manufacturing engines approaching the 2cm length provides many challenges—not necessarily with the jet itself, but with the components required to operate the jet. Millimeter-sized parts would require a 1-2 micron tolerance in order to have the dimension-to-tolerance ratio comparable to that of large-scale machining processes (Waitz 109). A ratio of this magnitude would require advanced micro-machining techniques.

Secondly, perhaps the most significant and technically challenging aspect of the micro-propulsion device is its limited residence time (Waitz 110). Once the combustion chamber size becomes 2 to 3 orders of magnitude smaller than that of a large scale jet engine, the residence time within the combustion chamber approaches the characteristic chemical kinetic time scale for hydrocarbon-air reactions. This is the large reason for moving away from traditional jet fuels and using hydrogen (Majumdar 68). In some cases, it may even be necessary to premix and preheat the fuel and air upstream of the combustion chamber in order to speed up the chemical kinetic time scale. It also has been suggested that increasing the combustion chamber size relative to the engine size will help with the very small residence times (Waitz 112).

2 Experimental Apparatus and Procedure

2.1 Pulsejet Design and Operation

Before the development of the 8 cm pulsejet came to fruition, much experimental work was conducted on a larger scale, 50 cm jet. Using scaling concepts derived from observing experiments on the 50cm jet, Michael Schoan, a fellow Mechanical and Aerospace Engineering graduate student at NCSU, developed a one-third scale model of the larger jet designed to operate at 15 cm. A similar concept was used in developing the 8cm jet. The smaller jet is a direct half scale model of the 15 cm jet with one exception: it was decided to leave the combustion chamber diameter the same as with the 15 cm model, creating a much larger combustion chamber-to-exhaust area ratio. In order to test various configurations, a plug for the combustion chamber was machined. When the plug is inserted, the 8cm jet becomes an exact half scale of the 15 cm jet. However, very little experimental data was taken with the plug inserted, none of which is referred to in this writing.

It is critical for the reader to keep in mind that when the author refers to scaling factors, the dimensions being scaled are the cross sectional areas of the inlet, combustion chamber, and exhaust, as well as the combustion chamber length. Each jet was designed so that the overall length of the jet (50 cm, 15 cm, 8 cm, etc.) could be varied with ease.

2.1.1 Pulsejet Geometry

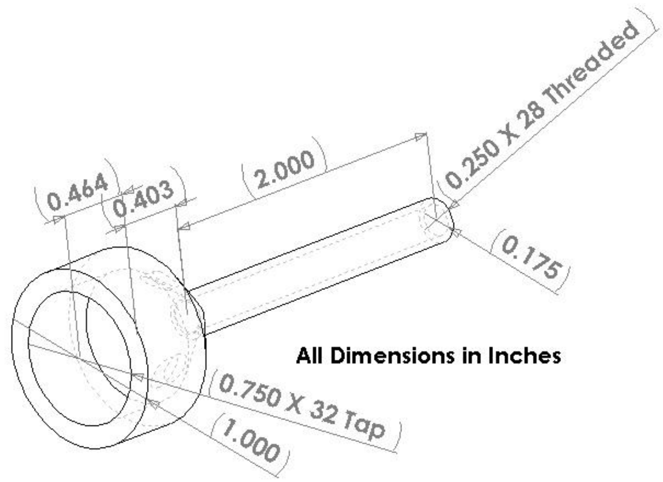

Figure 3: Isometric View of Pulsejet Dimensions

An isometric drawing of the 8cm pulsejet can be seen in Figure 3. Important dimensions to notice are the combustion chamber diameter (0.75 in—same as the 15 cm jet) and the exit diameter (0.175 in—half that of the 15 cm jet). At a later date, another pulsejet was machined with the same dimensions as the one above—the only exception being the exit diameter was reduced to 0.130 in. This was done to test the effects of a tighter exhaust on peak pressure rise and thrust. Also notice that the combustion chamber is tapped to allow the inlet to be inserted, and the exhaust is threaded to allow extensions to be added. All of the parts used with this jet were machined at the Mechanical and Aerospace Engineering Machine Shop on NCSU campus. A large part of the success of this thesis came about because of the punctual and accurate work done in this shop.

Figure 4: Conventional Inlet for 8cm Pulsejet

Pictured above in Figure 4 is the conventional inlet design for the 8 cm jet. The inlet diameter of 0.125 in is a half scale dimension of the 15 cm jet. This is the only conventional inlet geometry tested with this pulsejet. It is suspected but not known that varying the conventional inlet length and inlet diameter will allow the jet to run at slightly different frequencies and peak pressures, as is demonstrated with the rearward inlets.

The perpendicular inlet configuration served as a bridge between the conventional inlet setup and the rearward configuration. To create a perpendicular inlet, a 1/4x28 hole was tapped in the combustion chamber perpendicular to the axis of the jet. The inlet was a simple threaded rod with an eighth-inch hole drilled through it. Two different inlet lengths were tested: 0.4 and 0.3 inches. When the jet was tested in the perpendicular mode, the conventional inlet was replaced with a cap that screwed into the combustion chamber to close off the front.

Seen in Figure 5 is the jet in the rearward inlet configuration. One major difference between this configuration and previously mentioned configurations is that now two inlets are used instead of one. Similar to the perpendicular mode, when running the jet with rearward inlets, the same cap was used to seal off the front of the combustion chamber.

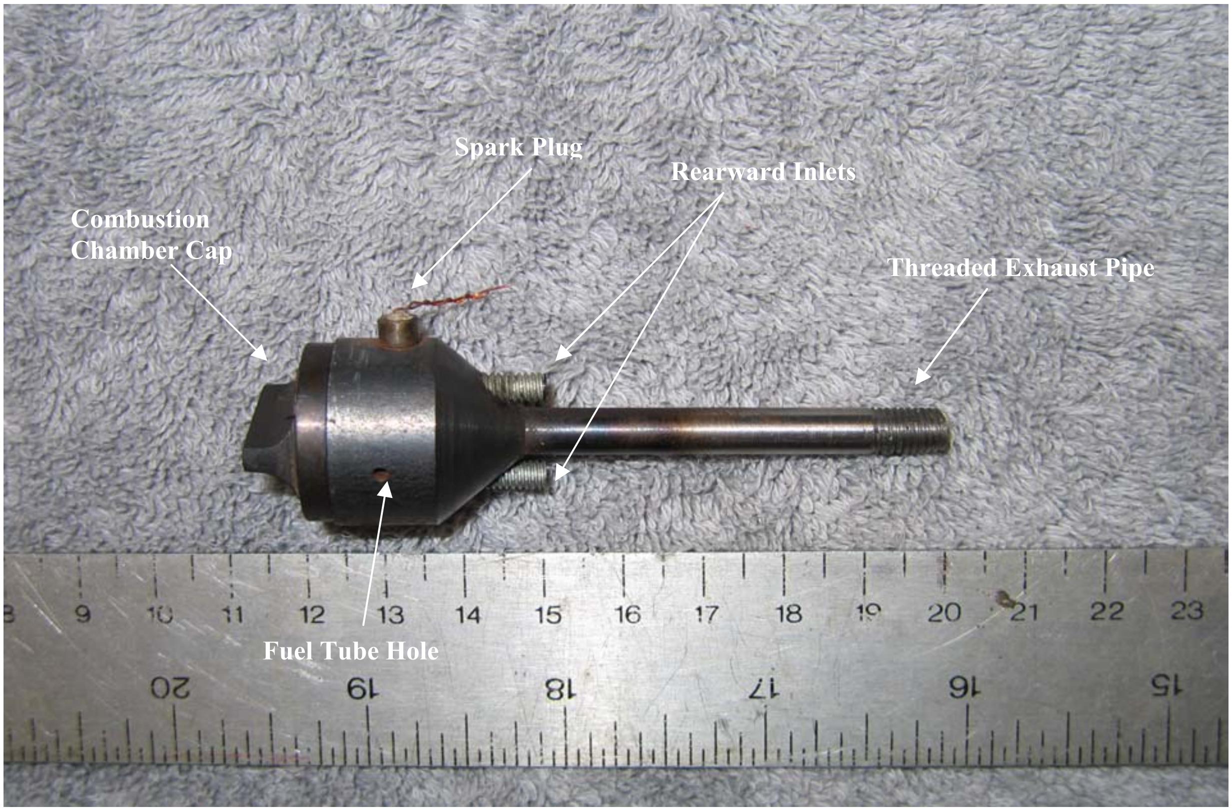

Figure 5: Pulsejet in Rearward Inlet Configuration

The two rearward inlets were designed so that their combined cross-sectional areas equaled that of the conventional inlet. This yielded a rearward inlet diameter of 0.088 in. The outside of these inlets are threaded with 10x32 thread count and screw into the angular section of the combustion chamber, as seen above.

2.1.2 Ignition Development

One of the many obstacles to overcome when scaling the pulsejet down was the development of an ignition system. For both the 50 cm and 15 cm jet a hobby spark plug was used. However, it immediately became clear that this spark plug would be too large for the smaller jets. In order to solve this problem, a mini-spark was machined using a steel rod and ceramic insert.

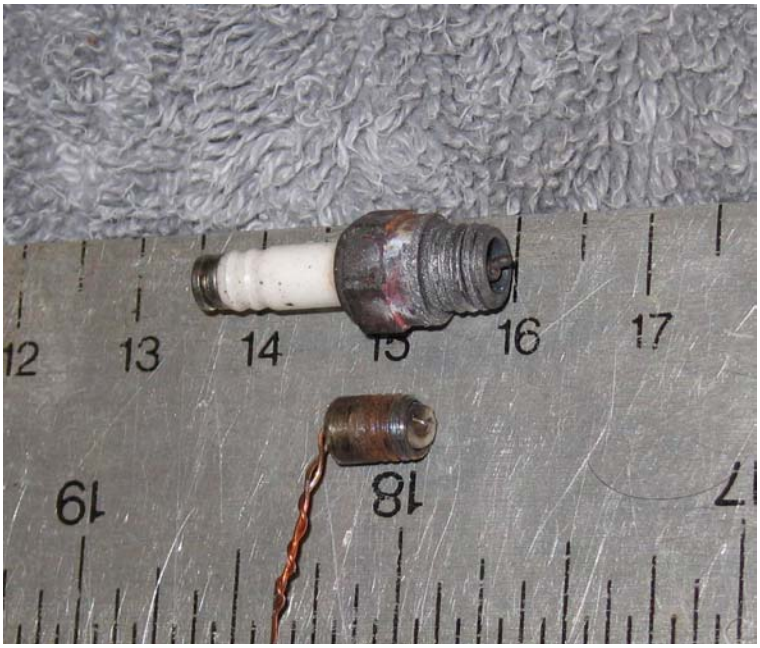

Figure 6: Hobby Spark Plug and Mini-Spark

Seen in Figure 6, the mini spark consisted of a steel tube with the outside threaded to a 10x32 thread count. The inside of the rod was drilled out so that a 1/8 in ceramic rod could slide through it. The ceramic rod has two tiny holes in it, allowing a copper wire to be fed through and create a loop. A 10x32 hole was drilled in the combustion chamber wall allowing the mini-spark to be easily inserted, as shown in Figure 5. When a high voltage source is applied, a spark will jump from the copper wire to the inside wall of the combustion chamber.

2.1.3 Fuel Delivery

As with the ignition system, finding the best method of providing fuel to the combustion chamber created a problem. For the 8 cm jet a 1/16 in stainless steel tube was used as the fuel line.

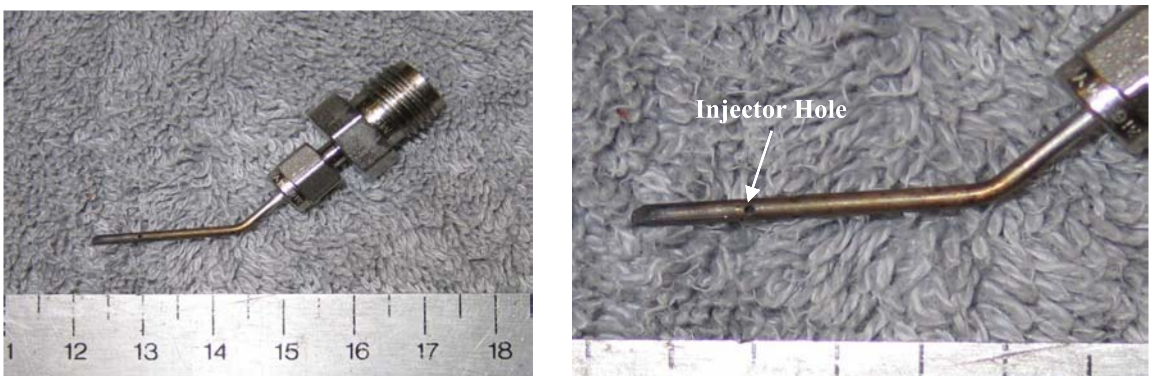

Figure 7: Fuel Tube

Figure 7 shows the 1/16 in tube along with the injector hole. The fuel tube has four holes drilled in the same location, allowing the fuel to be introduced in a "point-source" fashion. The end of the tube is sealed with a ceramic adhesive, not allowing any hydrogen to pass through. A 1/16 in hole was drilled in the combustion chamber wall, and the fuel tube slides easily into the chamber. The injector holes were drilled at a location such that when the fuel tube is inside the combustion chamber, the holes are at the center of the chamber, as shown in Figure 8.

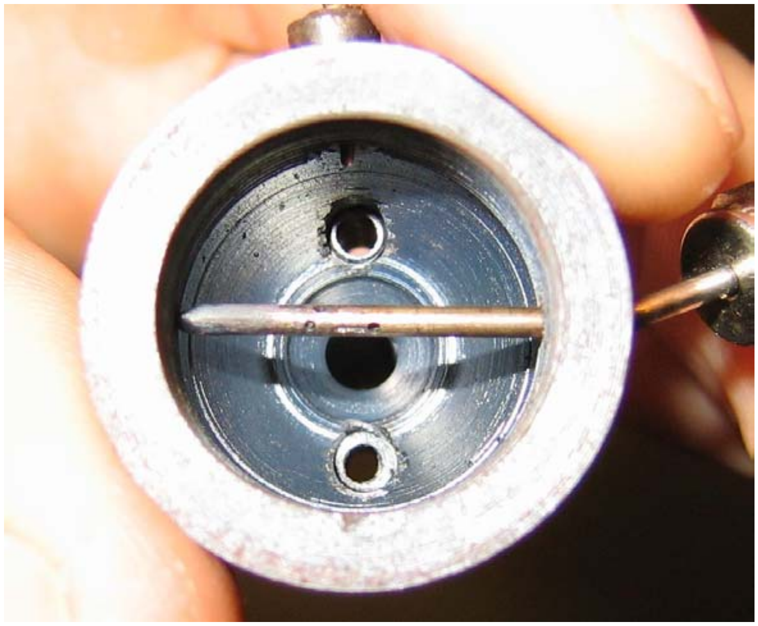

Figure 8: Fuel Tube inside the Pulsejet

2.1.4 Startup Process

As with any jet engine, the startup process can be difficult with the pulsejet—especially with a pulsejet 8 cm in length. However, as with any process, once it is perfected it becomes second nature. Listed below are the steps for starting the 8cm pulsejet:

1. Supply a steady stream of air into one of the inlet(s)
2. Turn on the high voltage source to create the spark
3. Slowly increase the fuel flow until the jet begins to operate
4. Turn off the spark and air flow to allow the jet to run on its own
5. To terminate the jet's operation, simply turn off the fuel source

The first attempts to start the pulsejet were done with in the conventional inlet configuration and were unsuccessful. These attempts were being done with an overall inlet length of 0.75 in, as opposed to the 0.40 in shown in the drawing above. The geometry change that started the 8 cm pulsejet for the first time was shortening the inlet length to its current length of 0.40 in. This was a suggestion made by Michael Schoan that had worked for him with his 15 cm pulsejet.

2.2 Experimental Setup when Measuring Pressure

Obtaining time-resolved combustion chamber pressure was a goal from the start of the 8 cm project. It was known from work in the larger, 50 cm jet that monitoring pressure throughout the jet's operation was the best way to validate operating frequency. In addition, measuring the peak pressure rises in the combustion chamber proved useful in determining the pulsejet's efficiency.

2.2.1 Pressure Transducer

Figure 9: Omega DPX101-250 Pressure Transducer

The pressure transducer used in the experiments was the Omega DPX101-250 Dynamic Pressure Transducer. With a one micro-second rise time, this model was ideal for measuring high frequency, pulsating pressures.

2.2.2 Transducer Mounting Technique

Purchased along with the pressure transducer was the Omega DPX-NPT flush mount for the pressure transducer. The transducer mounts smoothly in the DPX-NPT, which in turn mounts in a ¼-NPT connector. This allows the pressure transducer to be mounted onto a ¼ in pipe that can be screwed into the combustion chamber, as shown in Figure 10.

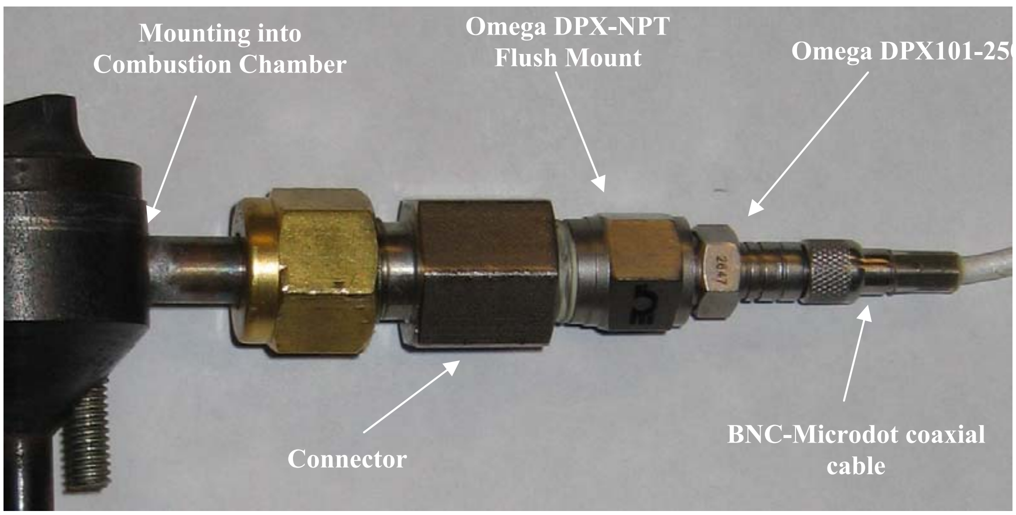

Figure 10: Pressure Transducer Mounting System

2.2.3 Oscilloscope Setup

Also purchased along with the pressure transducer were the ten-foot BNC-Microdot coaxial cable and the Omega ACC-PSI nine volt battery powered power supply. The BNC-Microdot cable screws onto the pressure transducer, as shown in Figure 10. The other end of the coaxial cable mounts to the power supply. A simply BNC cable connects the power supply to the oscilloscope.

The oscilloscope used was the Agilent Infiniium. With a sampling rate of two giga-samples per second, it proved to be a valuable tool when taking and analyzing data. In addition, the scope operates on Windows Operating System, which made organizing and acquiring data from the scope even easier.

2.3 Experimental Setup when Measuring Thrust

2.3.1 Load Cell

The load cell used when obtaining time-resolved thrust was the Kistler 3-Compent Force Sensor, seen in Figure 11. This load cell was borrowed from Dr. Terry Scharton and proved to be incredibly versatile. Able to measure time-resolved force data in all three axis, this device enabled the detailed analysis of how the pulsejet produces thrust—both positive and negative.

Figure 11: Kistler 3-Component Force Sensor

2.3.1 Load Cell Mounting System

As mentioned above, the Kistler load cell measures force in all three axis—one normal and two in shear. For the larger, 50 cm pulsejet, setting the load cell up in the normal direction worked sufficiently. However, for the 8 cm jet, it was decided to set the load cell up to measure thrust in the shear direction. This was concluded largely because of the mechanical resonance in the mount. Before each experiment, a resonance test was done that consisted of simply tapping on the jet and watching the force oscillations on the oscilloscope. If the resonance frequency of the mount was too close to the operating frequency of the jet (not more than half), then the measured thrust was a convolution of the actual time profile and the dynamics of the thrust stand. This rendered thrust data that was difficult to interpret.

In order to solve this problem, the load cell was bolted between two plates—the top one holding the jet and the bottom one mounted firmly to the test stand, as shown in Figure 12.

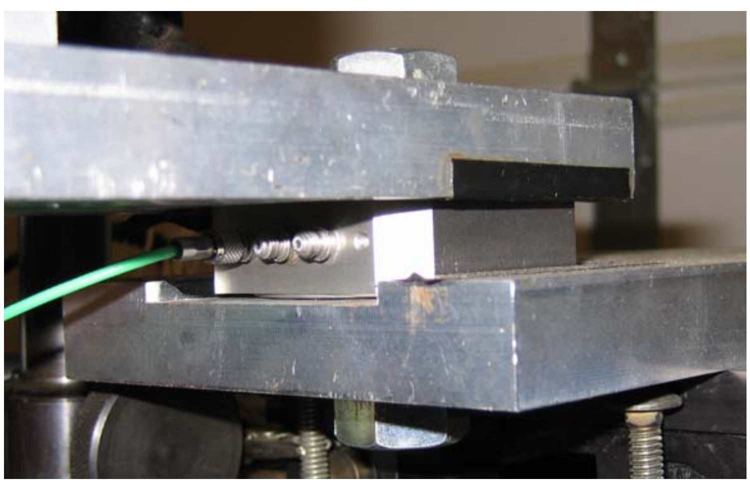

Figure 12: Load Cell Mounting System

This system proved to be the most efficient method of maximizing the resonance frequency in the thrust stand. The resonance frequency was measured between 2.2 and 2.5 kHz, while the jet operates between 1.0 and 1.2 kHz, depending upon its length.

Although the Kistler load cell provides a very effective way of obtaining time-resolved thrust, it is the opinion of the author that other options would be better suited for obtaining absolute thrust. Because of the interaction between the charge amplifier and the oscilloscope, it often proved difficult to be certain about the average value of thrust the pulsejet was producing. The setup would benefit from a very small, linear load cell with a long rise time—outputting the time-averaged thrust of the jet.

2.3.3 Oscilloscope Setup

The same oscilloscope was used when obtaining thrust as when obtaining pressure. Once again, this proved useful to be able to monitor thrust and pressure simultaneously on the same screen.

Unlike the pressure transducer, the load cell requires a charge amplifier in order to increase the power of its signal. A BNC-Microdot coaxial cable connects the load cell, as seen in Figure 12, to the charge amplifier. The charge amplifier in turn uses a BNC cable to connect to the oscilloscope.

3 Jet Operation Parameters with respect to Variance in Inlet Configuration and Exhaust Diameter

3.1 Changes in Operating Frequency as a Result of Inlet Variance

The fundament operating frequency of the pulsejet is primarily related to the overall length and follows a relationship like the one below:

$$f \sim \frac{1}{L}$$

Where "L" is the overall length and "f" is the fundamental frequency. It can easily be shown that when the pulsejet is longer, the frequency drops; the opposite can also be shown.

However, what is not as apparent is how the frequency of the pulsejet changes with variance in inlet length. It had to be determined if the frequency of the pulsejet varies when changing the jet from conventional mode to rearward mode. More importantly, an analysis of how moving from a single breathing inlet to two breathing inlets affects the jet's operation also had to be conducted.

3.1.1 Changes in Operating Frequency vs. Variance in Inlet Configuration

Figure 13 and Figure 14 show combustion chamber pressure traces of the pulsejet in two different modes. A careful examination of the data shows that the fundamental frequency of the pulsejet does not change—the highest peaks occur at the same rate.

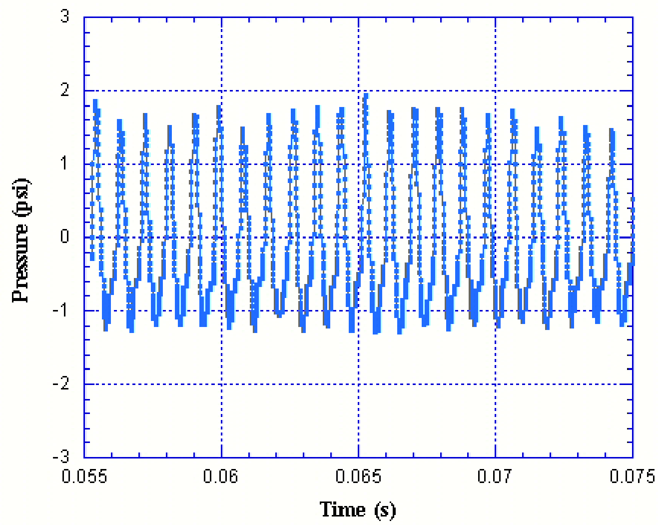

Figure 13: Conventional Inlet Configuration Pressure vs. Time

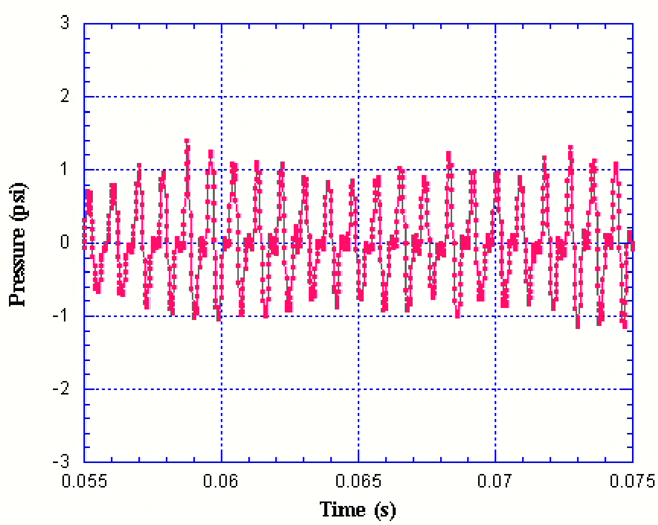

Figure 14: Rearward Inlet Configuration Pressure vs. Time, Inlet Length = 0.25in

However, an interesting phenomenon occurs with the rearward facing inlets. A close examination reveals there is a double frequency activity going on that occurs in between each of the higher peaks. This phenomenon occurs with the conventional inlet only at very low fuel flow rates. It is concluded that this is the appearance of the wave interactions within the inlet. In other words, the main operating frequency of the pulsejet is related to the overall length of the pulsejet. However, when two inlets are introduced pointing backwards, there exists a double frequency event that originates from the wave rarefaction within each inlet.

However, as the rearward inlet length increases, the significance of this event drops—the longer the inlet length, the less you see the double frequency event.

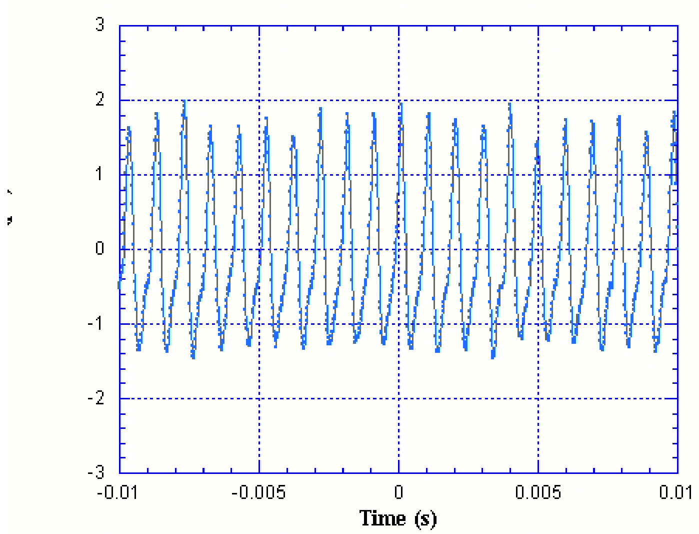

Figure 15: Rearward Inlet Configuration, Pressure vs. Time, Inlet Length = 0.50in

Notice in Figure 15 that doubling the inlet length (0.25in to 0.50in) causes the blip in the pressure traces to nearly vanish. As the inlet length increases, the wave interaction within the inlet becomes less obvious and is harder to distinguish between the combustion cycles.

3.1.1 Changes in Operating Frequency vs. Variance in Inlet Length, Rearward Configuration

While only one inlet was manufactured in the conventional configuration, several different lengths were manufactured and tested in the rearward configuration. As mentioned previously, each rearward inlet had a diameter of 0.088 in. Four different inlet lengths were tested--0.25, 0.35, 0.5, and 0.75 in. It should be noted that the outside limits (0.25 and 0.75 in) represent the inlet lengths at which the pulsejet will barely start. Therefore, it is assumed that the operating ranges of inlet lengths are fully covered in these experiments.

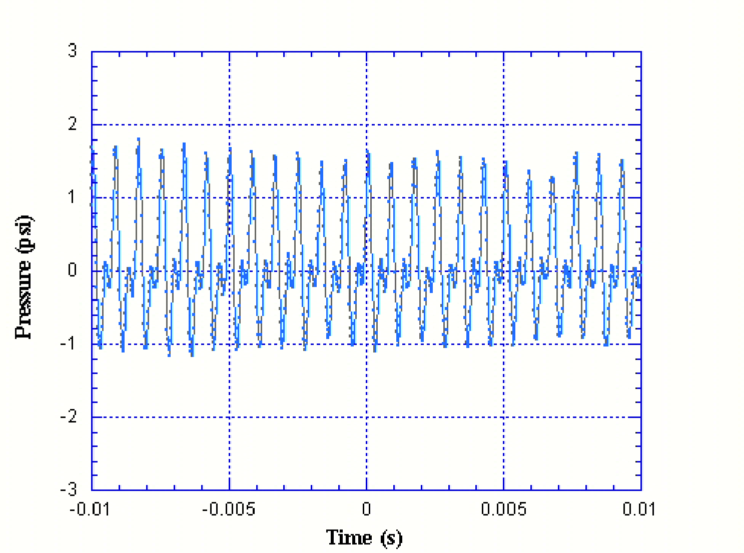

Figure 16: Pressure vs. Time, Inlet Length = 0.25 in

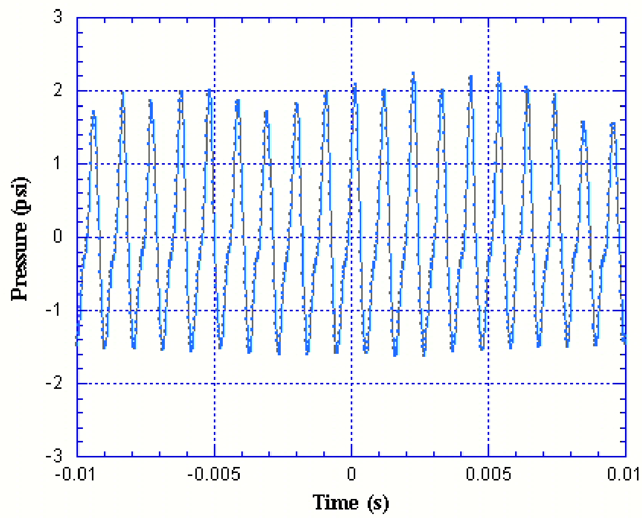

Figure 17: Pressure vs. Time, Inlet Length = 0.75 in, Overall Jet Length = 8 cm

A careful look at Figure 16 and Figure 17 reveals the slight change in operating frequency in the two configurations. The first plot, with an inlet length of 0.25 in, displays an operating frequency of 1200 Hz. Also, notice the double frequency event mentioned in the previous section. In contrast, the second plot has a frequency of 950 Hz. Similar to changes in overall length, when the inlet length is increased in the rearward configuration, the operating frequency of the jet decreases. Figure 18 shows how the operating frequency changes over the entire range of inlet lengths.

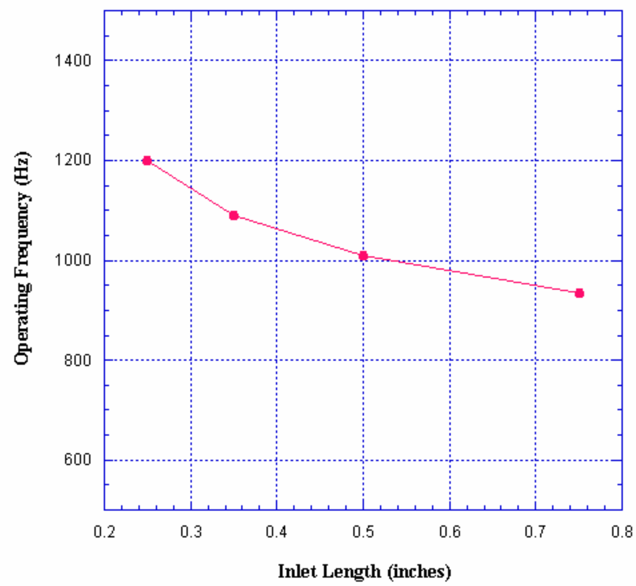

Figure 18: Operating Frequency vs. Inlet Length

It is interesting to note that the pulsejet operates at an average frequency of 1.0 kHz when its length is extended to 13.5 cm. Tripling the inlet length has nearly the same effect as making the overall length fifty percent longer.

3.2 Peak Pressure Rise as an Effect of Fuel Mass Flow

Throttle-ability of the pulsejet has been an issue throughout the history of its use. Unlike the conventional turbojet, it is difficult to determine the efficiency of the pulsejet at various fuel flow levels. In this writing, the author uses peak pressure variance to gauge the engine's performance; peak pressure rise referring to the average change in absolute pressure of the combustion chamber pressure trace.

The reader should note that all of the data discussed in this section refers to pulsejet with an exit diameter of 0.175 in. Comparisons to the smaller exit diameter pulsejet will be made in the next section.

3.2.1 Conventional Inlet Configuration

The majority of the tests in the pulsejet, including those shown in the plots above, were conducted at a fuel flow rate of 6.0 SLPM of Hydrogen. However, the pulsejet will operate at a rather large range of fuel flow rates. The 8 cm jet referred to in this writing will operate with fuel flows as low as 2.0 SLPM and as high as 7.0 SLPM of hydrogen.

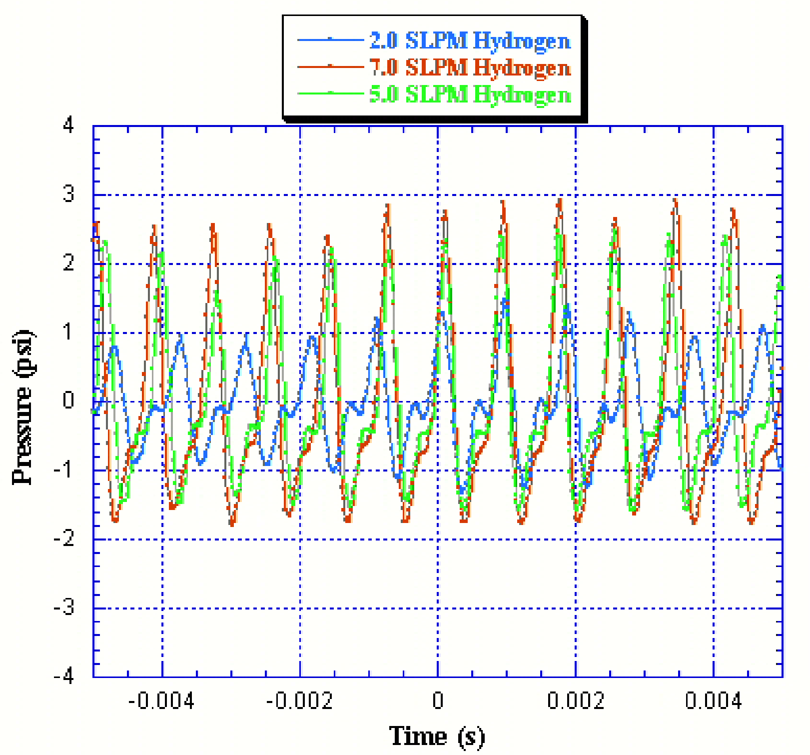

Figure 19: Pressure vs. Time at Various Fuel Flow Rates, Convention Configuration

Figure 19 shows how the pulsejet's combustion chamber pressure responds to changes in fuel flow rate. At 2.0 SLPM, the pulsejet is barely operating in pulsejet mode, as indicated by the very small pressure rise. Also, notice how the double frequency event shows up very clearly at the low end of the mass flow rate spectrum, as mentioned previously. As the fuel flow rate is increased, the double frequency blip drops away quickly. If the fuel flow rate is increased above 7.0 SLPM, the jet extinguishes itself and can no longer sustain self-operation.

The operating frequency of the jet varies with fuel flow rate only at the low end of the spectrum. Once fuel flow rate reaches 4.0 SLPM, the frequency of the pulsejet remains relatively stable. This can be observed audibly as well—when the pulsejet first starts at the lowest fuel setting, it sounds slightly different than the high-pitched hum that accompanies the jet at full throttle.

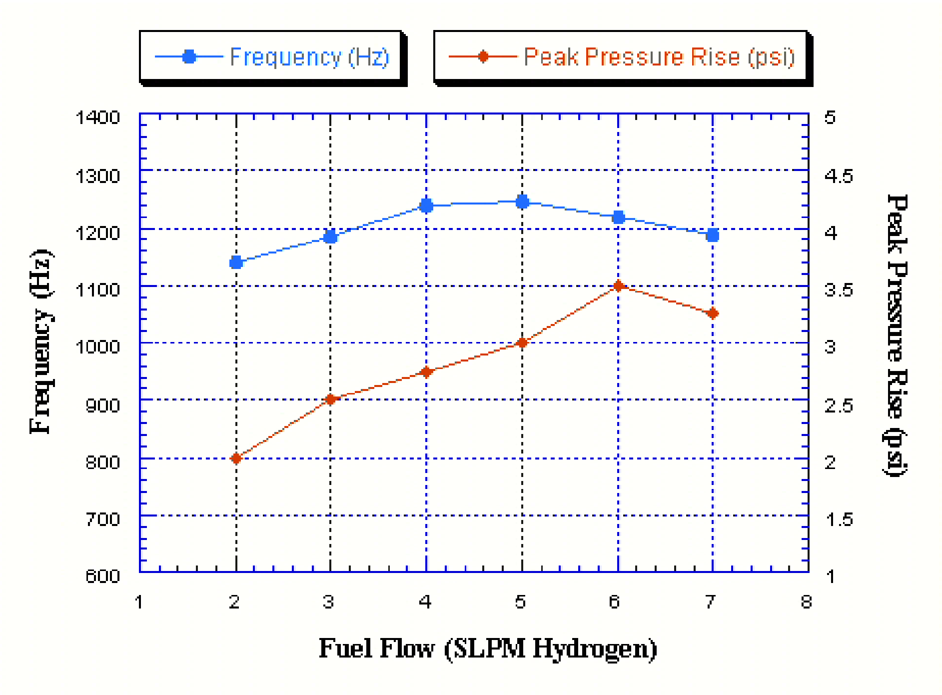

Figure 20: Frequency and Peak Pressure Rise vs. Fuel Mass Flow Rate, Conventional Configuration

Figure 20 shows a summary of the experiment conducted comparing the jet's behavior at various fuel mass flow rates. Based solely on the pressure traces, it is assumed that the jet operates most efficiently at the point of highest frequency and peak pressure—somewhere between 5.0 and 6.0 SLPM.

3.2.2 Rearward Inlet Configuration

The throttle-ability of the pulsejet changes drastically when the jet is operating in its rearward configuration. In contrast to conventional configuration, the operation range of the jet lies roughly between 4.0 and 6.0 SLPM of hydrogen. The jet will not start outside these fuel flow values, and varying the fuel flow outside these values once the jet has started results in the jet cutting off. This change in fuel flow range is most likely the result of poor mixing conditions with rearward facing inlets. The pulsejet is able to ingest much larger ranges of air when in the conventional configuration, enabling the pulsejet to operate over a larger range of fuel flow rates.

Figure 21 shows the pulsejet's combustion pressure traces at three different fuel flow rates in the rearward configuration. Although it is difficult to see visually from the plot, the operating frequency of the pulsejet changes in a similar fashion to that of the conventional configuration.

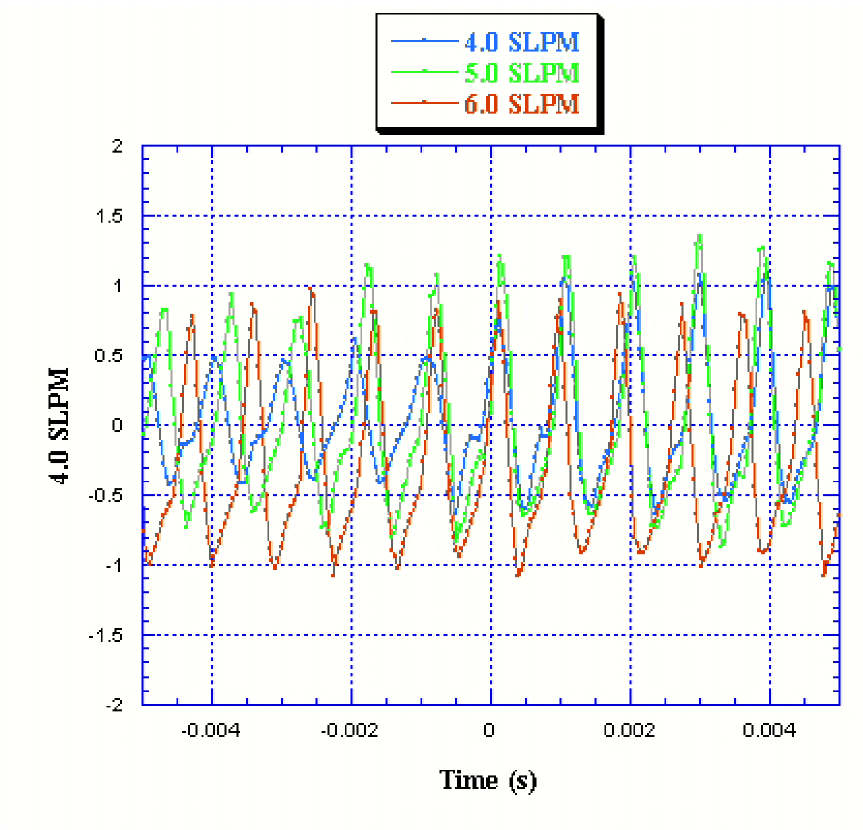

Figure 21: Pressure vs. Time at Various Fuel Flow Rates, Rearward Configuration

An important thing to notice in Figure 21 is the amplitude of the peak pressure rises. When compared to the traces shown in Figure 19, these peak pressure values are much lower than those of the jet in the conventional inlet configuration.

Figure 22 shows a summary of the pressure traces of the pulsejet in rearward configuration at its various fuel flow rates. As with the conventional configuration, the frequency steadily increases with increased fuel flow rate. As mentioned previously, this can be observed audibly as well as in the experimental data.

In contrast to Figure 20, the peak pressure rise shown in Figure 22 quickly reaches a steady value as the fuel flow rate is increased. The rearward inlet configuration does not allow the pulsejet to breathe as easily, thus creating a quenching effect as the jet begins to shut off at a lower fuel setting.

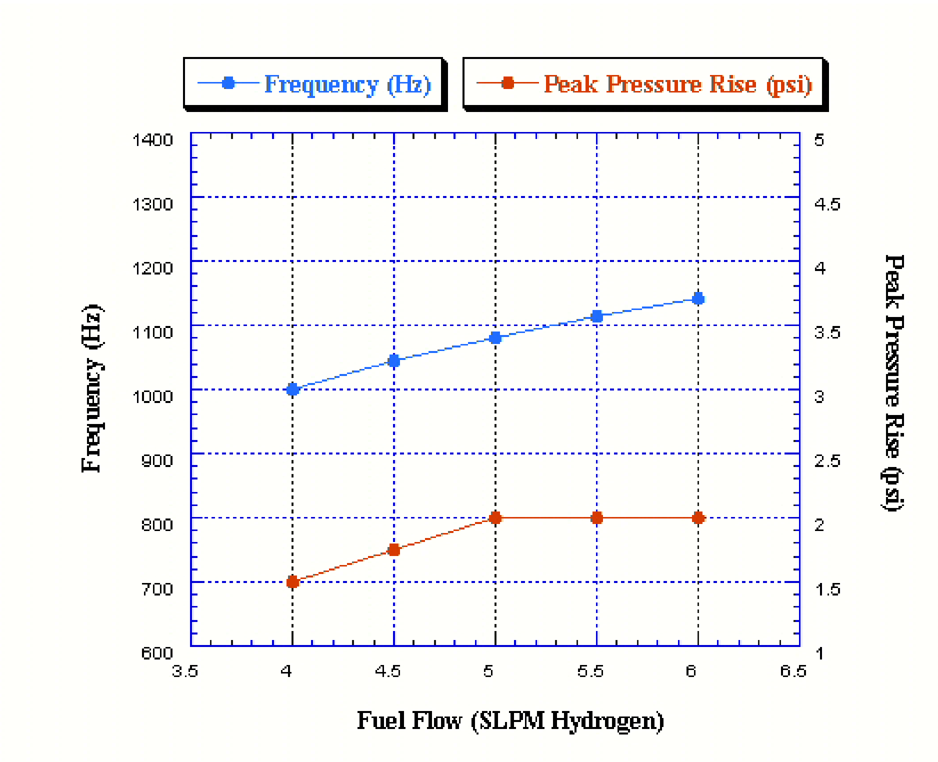

Figure 22: Frequency and Peak Pressure Rise vs. Fuel Flow Rate, Rearward Configuration

3.3 Comparisons of Jet Operation at Two Different Exit Diameters

As with any exhaust flow, reducing the exit diameter can cause dramatic changes in its flow properties. When dealing with a pulsejet, narrowing the exit diameter is not as easy as it seems. For example, when the exit diameter is reduced, critical design ratios such as combustion chamber-to-exit and inlet-to-exit are changed. In many cases this could mean the pulsejet will not start at all. With the larger scale jets it has been demonstrated that as the inlet diameter approaches the exit diameter, the combustion process does not build enough pressure and the pulsejet fails to start. Therefore, when manufacturing a pulsejet with a smaller exit diameter, it was critical that the design ratios fit inside the operational envelope defined by previous pulsejet work.

The two jets tested had exit diameters of 0.175 in and 0.130 in. All of the other components of the pulsejets were the same—including inlet areas. In addition, because the 0.130 in exhaust pulsejet will not start in the rearward configuration, all of the data discussed below refers to the conventional configuration.

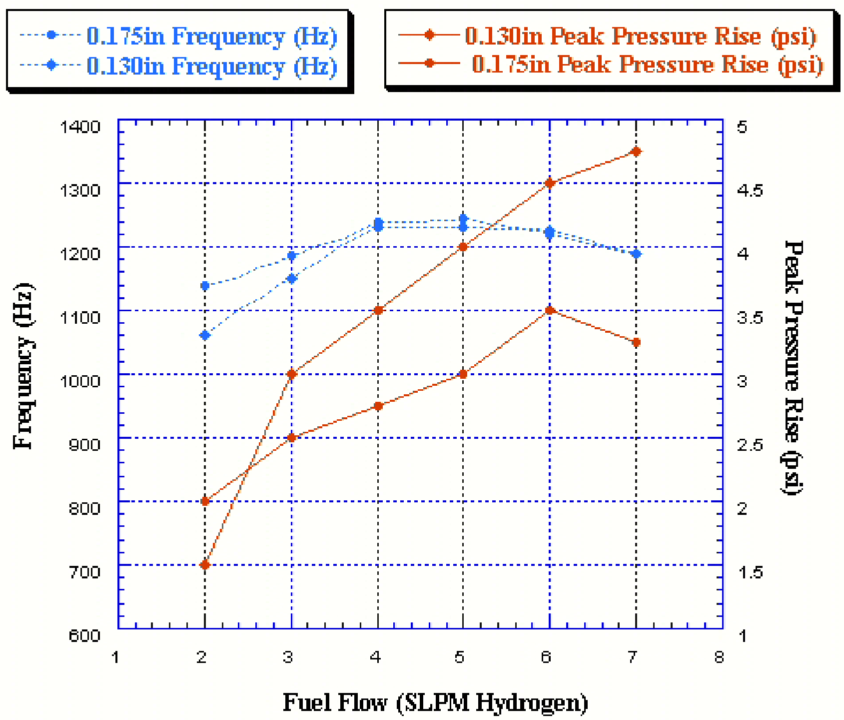

Figure 23: Comparisons of Jet Operation at Two Different Exit Diameters, Conventional Inlet Configuration

As seen in Figure 23, the operating frequency of the pulsejet has a very small dependence on exit diameter. This is expected, as the frequency is associated the fundamental frequency of the inlet and exit—both of which are length dominated. On the other hand, notice the large difference in peak pressure rise. This is also expected—the smaller, more contracted exit should result in a higher combustion chamber pressure build up.

4 Analysis of 8 cm Pulsejet Net Thrust and Specific Fuel Consumption

It had been previously investigated on the 50 cm pulsejet whether or not the jet's cyclical thrust phenomenon produced any negative thrust. It was demonstrated through Laser Doppler Velocimetry (LDV) experiments that the exhaust velocity of the 50 cm pulsejet cycles between positive and negative values in a sinusoidal fashion. This knowledge was the primary impetus in using the Kistler 3-Component Force Sensor—monitoring the time-resolved thrust enabled an investigation of how the pulsejet's thrust reacts to the combustion chamber pressure.

All of the thrust data discussed in this section refers to the 8 cm pulsejet with an exhaust diameter of 0.175 in. The smaller diameter pulsejet was not tested because it will not start in the rearward inlet configuration.

4.1 Mechanical Resonance of Test Stand

A major problem with measuring time-resolved thrust for the 8cm pulsejet was the elimination of mechanical resonance of the test stand. Because the 8cm pulsejet operates at a relatively high frequency, the stiffness of the load cell and the overall weight of the mounting plate played an important part in obtaining unambiguous data.

Figure 24 shows a plot of the resonance in the test stand. The frequency of the major oscillations is approximately 2.1 kHz—roughly twice the operating frequency of the pulsejet.

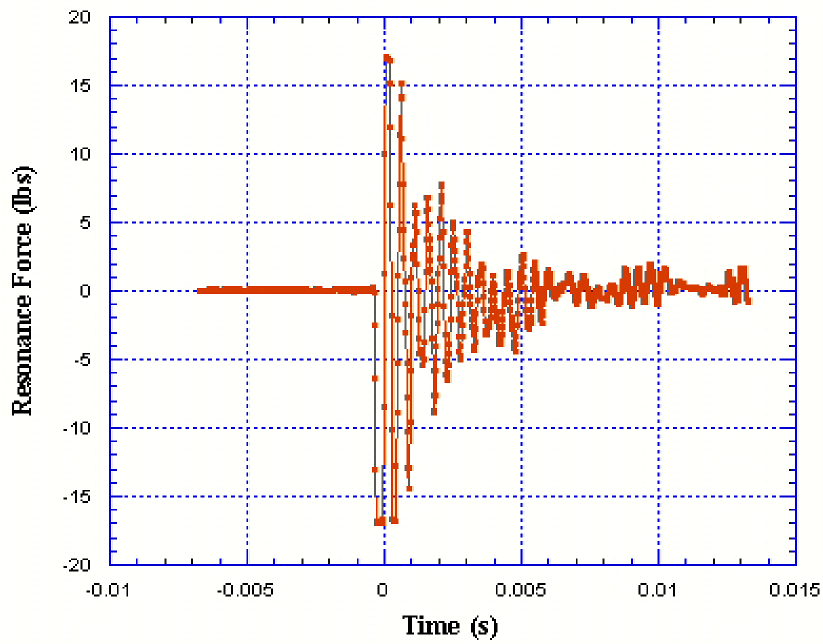

Figure 24: Thrust Test Stand Mechanical Resonance Measurement

4.2 Thrust in the Conventional Inlet Configuration

Because the inlet faces forward in the conventional configuration, it is expected that the resultant net thrust should be very small due to the expelling of combustion products in the forward direction. Figure 25 shows the time-resolved thrust of the 8 cm pulsejet in the conventional inlet configuration. It can be seen from the plot that the average thrust is very small—so small, in fact, that it falls within the threshold of the load cell and is difficult to determine as real.

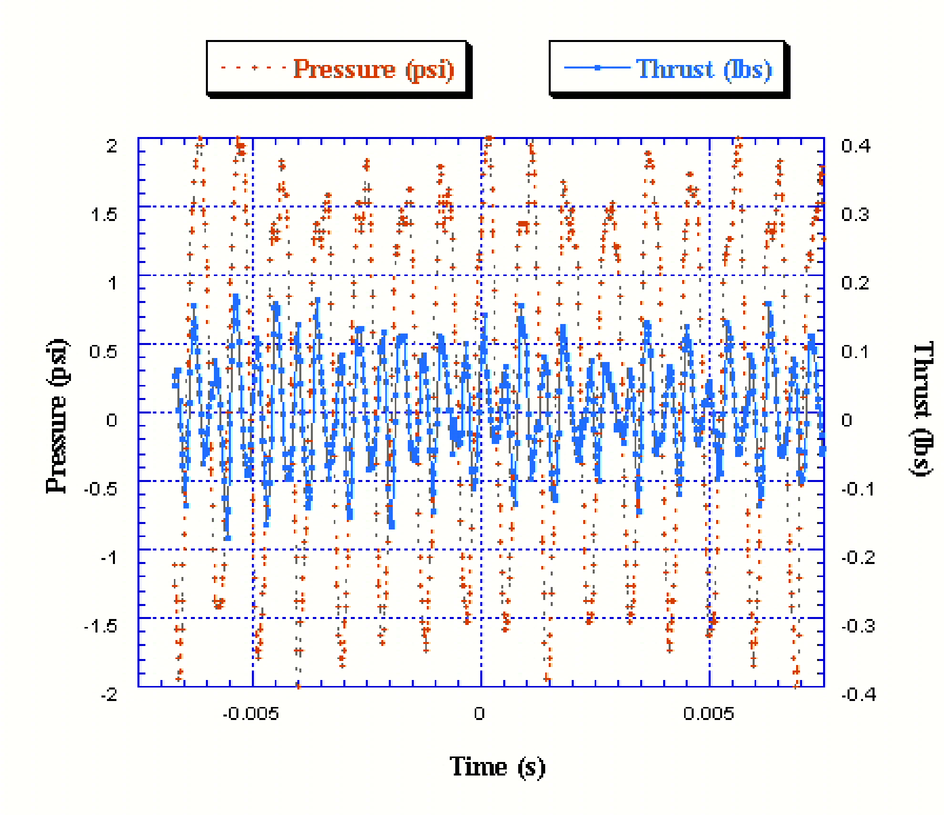

Figure 25: Conventional Configuration Thrust Overlaying Combustion Chamber Pressure, 6.0 SLPM Hydrogen

Figure 26 shows a closer look at the thrust time history on a finer time scale. An interesting and disturbing result can been seen in this plot—the thrust frequency appears to be double that of the pressure trace. As the pressure begins to fall below atmospheric, the pulsejet appears to produce a sudden burst of positive thrust. One theory explaining this, proposed by Dr. Terry Scharton, centers around the idea that the amount of time required for combustion products to be expelled out the inlet(s) is very small when compared to those being expelled out the exhaust. Hence, a combustion event produces instantaneous thrust from the inlet before the exhaust flow has time to exit the jet. In addition, the resultant low pressure in the combustion chamber would create reverse flow in the inlet still before the effect of the exhaust flow is felt. Finally, after one thrust oscillation, the exhaust flow reaches the exit and creates another positive burst of thrust. Because a large concern is the mechanical resonance of the thrust stand, this phenomenon needs to be investigated to determine if it is real or is the result of a resonant interaction between the thrust stand and the pulsejet.

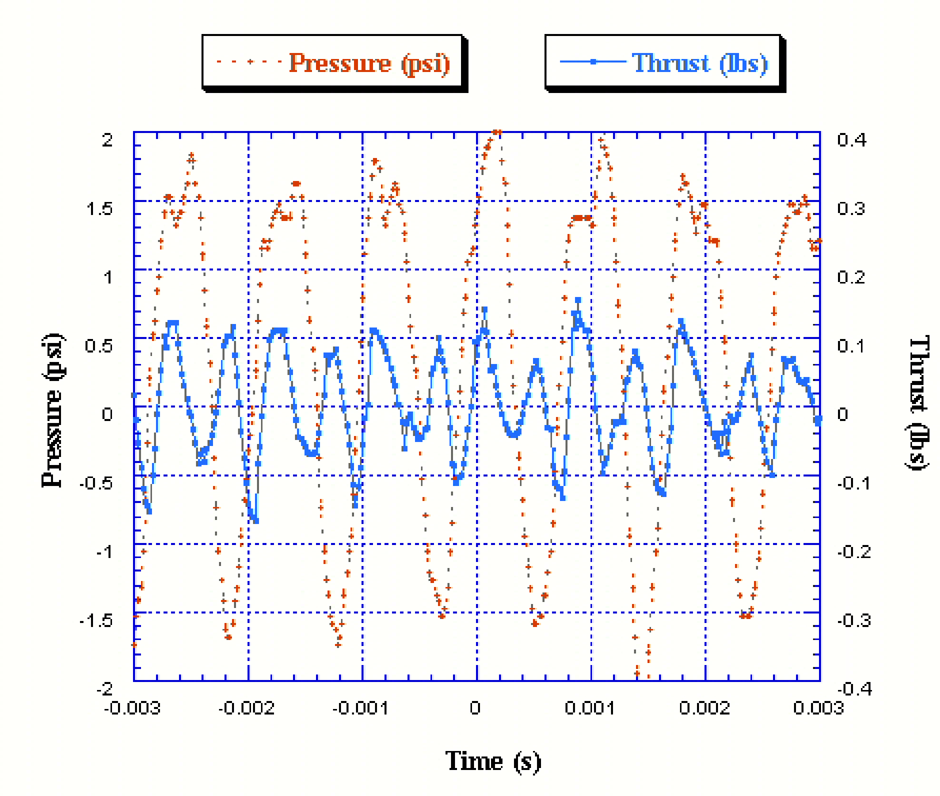

Figure 26: Conventional Configuration Thrust Overlaying Combustion Chamber Pressure, Higher Temporal Resolution, 6.0 SLPM Hydrogen

4.3 Thrust in the Rearward Inlet Configuration

In the rearward configuration, all of the products from the combustion chamber are being expelled in the downstream direction. Of course, during the sub-atmospheric air ingestion phase, the momentum flux is in the opposite direction and produces a negative thrust component. However, this component should be small when compared with the positive component of the exhaust flow due to its much lower velocity. The result should reflect the highest net thrust of all the configurations.

Figure 27 shows the time history of the pulsejet's thrust in the rearward inlet configuration. The thrust curve has an average thrust of 0.19 lbs (the threshold of the load cell is +/- 0.001 lbs), yielding a thrust specific fuel consumption of 0.198 lbm/lbf-hr.

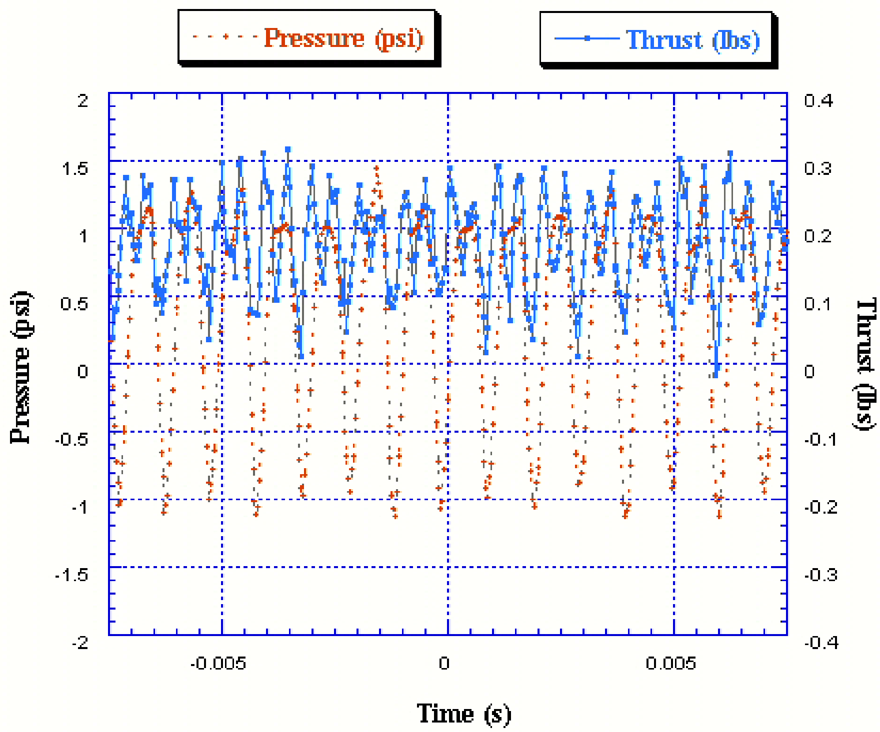

Figure 27: Rearward Configuration Thrust Overlaying Combustion Chamber Pressure, 5.0 SLPM Hydrogen

The rearward thrust trace at higher temporal resolution can be seen in Figure 28. Although the thrust data is not as "clean" as that of the conventional configuration, the thrust measurements are at a frequency that is twice that of the pressure trace.

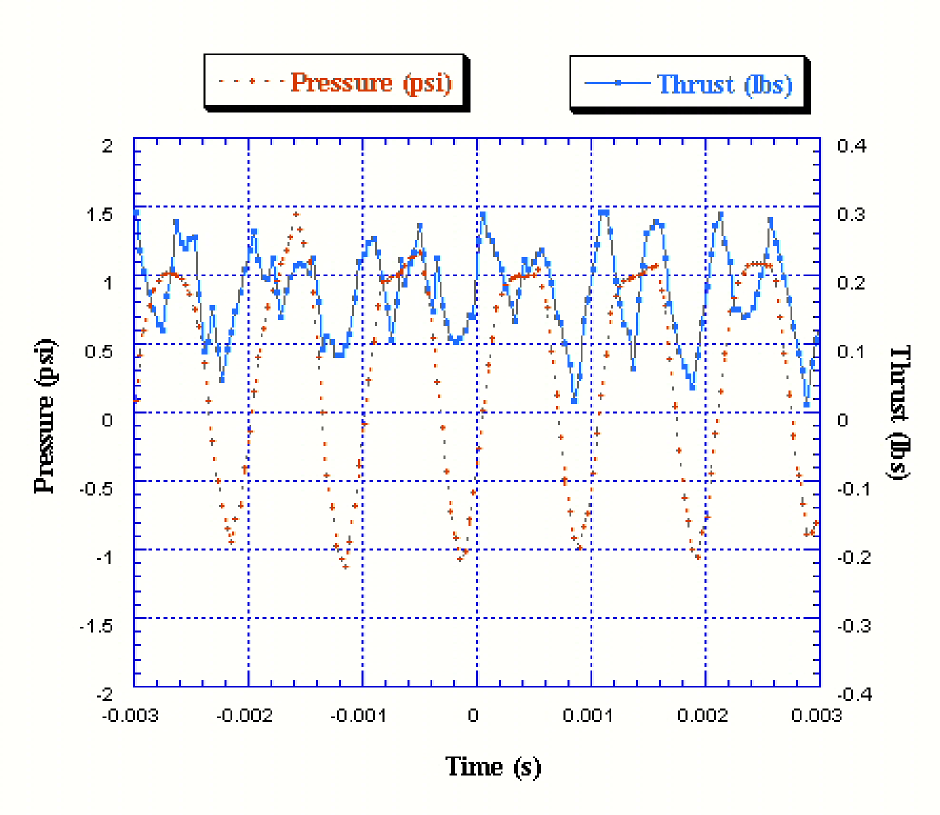

Figure 28: Rearward Configuration Thrust Overlaying Combustion Chamber Pressure, Higher Temporal Resolution, 5.0 SLPM Hydrogen

5 Operation of Five-Centimeter Mini-Pulsejet

5.1 Five-Centimeter Pulsejet Design

After the 8 cm pulsejet became operational, the next step in achieving the main objective of 2 cm was the development of a 5 cm jet. The 5 cm pulsejet very closely resembles its 8 cm counterpart in that all of the dimensions of the combustion chamber are an approximate two-thirds scale of the larger jet, giving it a diameter of 0.50 in. The overall length was chosen at 5 cm, and, as shown in Figure 29, the tip of the exhaust was threaded to allow the use of various extensions.

Figure 29: 5 cm and 8 cm Pulsejets

The exhaust diameter is 0.150 in, the conventional inlet diameter is 0.080 in, and the inlet length is 0.170 in. In the rearward inlet configuration, each inlet length is approximately 0.20 in and the inlet diameter is 0.055 in, keeping the inlet-to-exit area ratio within the known operational limits. An interesting thing to note is that the rearward inlets do not face straight back. This is because for this pulsejet, the rearward inlets were a modification and not an initial design parameter. Machining straight back inlets into an angled surface was deemed extremely difficult on such small a scale, so the inlets were drilled perpendicular to the angled surface and face approximately 135 degrees back from the flight direction. As will be discussed later, the inside of this pulsejet has been electroplated with platinum. Because the platinum plating process was not readily available nor inexpensive, straight back inlets were never tested.

Figure 30: Frontal View of 5 cm Pulsejet

The 5 cm pulsejet uses the same spark plug design as its larger counterpart, as shown in Figure 30. The reader should note from this picture that one of the many problems when developing mini-pulsejets is how difficult it becomes to handle such small components. Simple tasks like experimental setup become very time consuming.

5.2 Five-Centimeter Pulsejet Operation

The first attempts to test the 5 cm pulsejet were done in the conventional configuration and were unsuccessful. The starting procedure is the same as the 8 cm jet, but the 5 cm jet would not sustain operation without the help of forced air into the inlet. The conventional inlet length was decreased as much as the design would allow, and the pulsejet still would not operate without aid.

Upon the advice of Dr. William Roberts, the 5 cm pulsejet was sent to Artisan Plating in Leonard, Michigan to have the combustion chamber walls electroplated with a 5 micron platinum coating. It was the hope of the author that the platinum would speed up the combustion process enough to enable the pulsejet to sustain operation without forced air. Unfortunately, when testing in the conventional configuration, the platinum appeared to have no effect—the pulsejet behaved exactly the same.

Coincidentally, it was at this time that the testing began on the 8 cm pulsejet in the rearward configuration. With the help of Skip Richardson and Mike Breedlove in the NCSU machine shop, a modified rearward inlet configuration was machined into the angular section of the 5 cm pulsejet. The two inlets were designed to have the same total cross-sectional area as the initial conventional inlet. A cap for the combustion chamber was also machined.

The 5 cm pulsejet will sustain operation without forced air only in the rearward configuration. In fact, using the cap on the combustion chamber, the overall length of the jet can be reduced as low as 4.5 cm and still enable successful operation.

Because of the extremely small scale and because of the time frame of this research, no experimental data was obtained from the 5 cm pulsejet. It is suspected that a new mounting technique would be needed for the pressure transducer—the current technique would increase the overall combustion volume by a significant fraction. In addition, because of the even higher frequency, special care would need to be taken when measuring both time-resolved and time-averaged thrust.

6 Conclusions

It should be noted by the reader that the objective of this research was to develop a working pulsejet on as small a scale as possible. Because there have not been many breakthroughs in the micro propulsion field, getting a pulsejet to start at a length of 8 cm is a large accomplishment in itself. This research is unique in that it represents the first known development of a pulsejet on a scale this small. Furthermore, acquiring any experimental data was an added bonus. The conclusions obtained from this research are listed below.

Operating Frequency

1.) The operating frequency of the pulsejet scales as one over the inlet length—ranging from 1.2 kHz at 0.25 in to 950 Hz at 0.75 in. Tripling the inlet length has nearly the same effect as increasing the overall length by fifty percent.

2.) Reducing the exhaust diameter of the pulsejet has very little effect on its operating frequency—only at the lower fuel settings can any noticeable difference be observed.

3.) The operating frequency of the pulsejet drops at its lower fuel settings, but remains fairly steady at the upper range.

4.) When in the rearward configuration, an inlet length of 0.25 in produces a double frequency "blip" in the pressure trace. This event can also be seen at the lower fuel settings in both configurations. It is concluded that the "blip" is the result of wave interaction inside the inlets. As the inlet length is increased, or the fuel flow is increased, the wave interaction that produces the "blip" becomes less pronounced and fades away.

Combustion Chamber Peak Pressure Rise

1.) Fuel flow rate has a direct effect on the peak pressure rise—the lower fuel settings produce a much lower change in combustion chamber pressure. In the rearward configuration, the peak pressure rises continually with fuel flow until the jet cuts off. In contrast, when in the conventional configuration, the peak pressure rise reaches a maximum around 6.0 SLPM—before the jet cuts off.

2.) Reducing the exhaust diameter from 0.175 in to 0.130 in has a very noticeable effect on the peak pressure rise. The larger diameter has a maximum peak pressure value of 3.5 psi, while the smaller diameter reaches a maximum value of 4.75 psi.

Thrust

1.) When the pulsejet is operating in the conventional configuration, the average thrust is very close to zero—0.004 lbs. This is expected because the inlet faces forward and any combustion products expelled out the inlet are counterproductive to positive thrust.

2.) The pulsejet produces positive net thrust when in the rearward configuration. The average thrust value is 0.19 lbs, and the thrust specific fuel consumption is 0.198 lbm/lbt-hr.

3.) The peaks in the thrust occur at twice the frequency as the pressure. Because of concerns with mechanical resonance in the thrust stand, this raises questions about experimental setup independent the data is. It is unknown at this time whether the double frequency is real or if it is the result of resonance interaction inside the thrust stand.

4.) Measuring time-resolved thrust is very difficult because it is nearly impossible to develop a testing system with a mechanical resonance high enough to totally trust the data obtained.

Five-Centimeter Pulsejet

1.) The 5 cm pulsejet will not operate in the conventional configuration. It is suspected that this is due to mixing problems stemming from the single inlet. Because of the small size, the conventional inlet approaches a thin wall with a hole in it. The rearward facing inlets allow the pulsejet to breathe more freely.

2.) The 5 cm pulsejet used in this research contains a 5 micron platinum coating on the inside of the combustion chamber walls to act as a catalyst for the combustion process. The platinum coating and the modification of the pulsejet to allow for rearward configuration testing were the major steps taken to achieve operation without forced air.

7 Future Work

Although there has been extensive pressure and thrust data documented in this work, there has been little work done in optimizing the pulsejet's operation based around the jet's thrust capabilities. This process should be made in an attempt to prepare the pulsejet to become flight hardware. The first step in this process would be to acquire a linear load cell capable of measuring thrust down to hundredths of inches. This would eliminate any problems with the mechanical resonance in the test stand, and would provide a much more reliable time-averaged thrust.

When testing the pulsejet for optimal thrust, the jet would need to be tested in several different modes and geometries. Changing the overall length of the jet, exit diameter, and exit geometry would be interesting topics to investigate. The end result would need to produce the best match between highest thrust and acceptable thrust specific fuel consumption, as well be easy to start and reliable during operation.

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