COLD FLOW TESTS OF A THRUST AUGMENTED PULSE DETONATION
ROCKET EJECTOR

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COLD FLOW TESTS OF A THRUST AUGMENTED PULSE DETONATION ROCKET EJECTOR

by

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ABSTRACT

COLD FLOW TESTS OF A THRUST AUGMENTED PULSE DETONATION ROCKET EJECTOR

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Supervising Professor: Dr. Donald R. Wilson

A concept has been proposed for the adaptation of a pulse detonation rocket (PDR) into a type of scramjet in which the PDR ejects into a subsonic or supersonic secondary flow as a means of providing thrust. A model of such a configuration was developed and tested in the supersonic blow-down tunnel at the Aerodynamics Research Center (ARC) at the University of Texas at Arlington (UTA). This was done as a means of determining if this is a viable option for future propulsion.

All Mach 0 tests indicate that unsteady ejector performance is better than steady performance as was expected. Quantifiable results for thrust augmentation were obtained, but proved to be too optimistic when compared to data from other similar
studies. A more accurate prediction of thrust augmentation could not be used due to the lack of knowledge of total pressure in the mixing interface, but it was determined that the secondary flow is relatively insensitive to the primary flow fluctuations, and higher frequency ejector rates drive the system to results closer to steady-state. As for supersonic test results, there was little to no effect on the secondary flow from the primary flow due to the large mass flow ratio between the secondary flow and the primary flow.
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CHAPTER 1

INTRODUCTION

1.1 Background

Pulse detonation engines (PDE) and pulse detonation rockets (PDR) have been researched extensively as an alternate form for high-speed propulsion. A concept has been proposed for the adaptation of a PDR into a type of scramjet in which the PDR ejects into a subsonic or supersonic secondary flow as a means of providing thrust. A model of such a configuration was developed and tested in the supersonic blow-down tunnel at the Aerodynamics Research Center (ARC) at the University of Texas at Arlington (UTA). This was done as a means of determining if this is a viable option for future propulsion.

The first step is to conduct “cold-flow” simulations in which the gas cycles in the PDR chamber are left undetonated to provide a baseline for future experiments. As a means of safety, atmospheric air is used to replace the fuel and the oxidizer in the combustion mixture. That is the basis for this research and thesis.

1.2 Multi-mode Propulsion Concept

In the National Aerospace Plane program, as well as other hypersonic vehicle proposals, one of the major obstacles that must be overcome is the development of a propulsion system that can easily transition between all flight regimes. A propulsion
system for this type of application is needed to start at rest, accelerate through the transonic region, and continue to accelerate to a hypersonic cruise or even escape the sensible atmosphere.

One novel approach to solving this problem is a multi-mode propulsion concept proposed in Munipalli et al.\textsuperscript{[1]}. This system proposed takes advantage of ejectors and detonation physics as a means of providing thrust. This system operates with four distinct modes (Fig 1.1) as shown below.

Mode 1 - Ejector-Augmented PDR

Mode 2 - Pulsed Normal Detonation Wave Engine

Mode 3 - Steady Oblique Detonation Wave Engine

Figure 1.1 Modes of operation for the engine concept
As seen, the first mode is an ejector-augmented pulse detonation rocket that will be implemented for take off to low supersonic Mach numbers. The strut stationed near the inlet will house the pulse detonation rocket ejector (PDRE) and eject into the surrounding air. Because of the nature of PDR devices, this will be a cyclic, unsteady-state device.

The second mode is a pulsed normal detonation wave engine (NDWE) for high supersonic and low hypersonic Mach numbers. The strut will no longer function as a PDRE, but will change roles to a hydrogen injector. Detonation will occur further downstream just forward of the nozzle throat, and propagate upstream into the fuel/oxidizer mixture.

The third mode of the device will induce steady-state oblique detonation waves in the engine duct as the burning combustion process for the fuel and air when conditions are such that the internal Mach condition in the engine is greater than that of the Chapman-Jouguet Mach number associated with detonation waves.

The last mode, not shown, will implement a pulse detonation rocket (PDR) in the strut mounted ejector when the breathable atmosphere can no longer support an air-breathing device.

The obvious advantage to this is that all modes can make use of the same internal geometry, eliminating the need for additional flow paths. Another added bonus is the fact that the atmospheric air entering the duct does not have to be slowed to subsonic speeds at higher Mach numbers. This will greatly reduce the losses in total pressure associated with shock waves and, in turn, increase efficiency of the engine.
Shock waves also increase the static temperature, and without them, the gas temperature can be maintained below the fuel auto-ignition temperature.

A great number of these concepts have yet to be explored, but the first mode of a PDRE, will be the main focus of the experiments represented here.

1.3 PDR Mechanics

The PDR itself is a rather simple device. The majority of the system is a duct that is closed at one end. There is a valve or set of valves that governs the timing of the fuel and oxidizer flow into the duct, and a high-voltage ignition system that is used to initiate the detonation.

It is the detonation combustion process that makes a PDR unique in propulsion applications. Detonations are supersonic combustions that can be modeled as a shock wave followed by a flame front, and an entire PDR has to be designed around this phenomenon.

1.3.1. PDR Cycle

A typical cycle for a PDR consists of four distinct phases. The first phase consists of filling the chamber with a fuel/oxidizer mixture subsonically at some pressure, $P_1$, greater than ambient pressure, $P_0$. It is critical that the fuel and oxidizer are well mixed and stochiometric to ensure combustion.
Figure 1.2 Phase 1: filling the chamber with fuel and oxidizer

At some point the valve is shut off at the end creating a boundary condition of zero velocity at the closed end of the chamber. This initiates rarefaction wave propagation downstream through the chamber.
Figure 1.3 Phase 2: detonating the mixture

At some point, a detonation is induced in the mixture. The detonation wave propagates supersonically down the chamber. As it travels downstream, the disparity in velocity of the flow becomes quite large through the chamber creating more rarefaction waves through the device.
Figure 1.4 Diagram of the pressure distribution upon detonation

Since the detonation wave acts as a shock wave, it provides compression of the gas as it passes through what is known as the Von Neumann pressure spike. The initial compression is shortly followed by a heat addition to the flow. Because of the compression, the static pressure after the detonation wave, $P_2$, is greater than both $P_1$ and $P_0$. As the flow expands due to the rarefaction waves, the pressure far upstream of the detonation wave, $P_3$, is less than $P_2$, but still larger than the ambient pressure, $P_0$ of the outside air.

This pressure difference continues to drive the flow once the detonation has left the chamber.
Figure 1.5 Phase 3: blow-down of chamber

At this point, the rarefaction waves propagate upstream as a means of exhausting the residual gases.

Once the tube has reached ambient or near-ambient conditions, a small fill of purge air is injected into the system.

Figure 1.6 Phase 4: purge air fill

The purge air is only meant to be a buffer between the burnt slug of gas from the previous cycle and the undetonated fuel and oxidizer coming into the chamber for the next cycle. This prevents the incoming slug from burning prematurely from the high temperature.

The cyclical process can be driven to high frequencies, making the thrust produced by the system a quasi-steady-state effect.
1.3.2. Benefits

The reason PDR devices are beneficial has to do with the properties of the detonation itself.

Detonations are only one type of combustion process. The other is deflagrations. Detonations, as seen in the PDR cycle, are characterized by high supersonic flame speeds and large pressure changes. Due to the high rate of propagation, a detonation can be closely approximated as a constant volume process and modeled as part of the Humphrey cycle. This is quite different from the more common deflagration combustion process that is approximated as isobaric following the Brayton cycle. Further, the propagation speeds are usually in the low subsonic regime.

![Figure 1.7 Pressure/volume graph of the Brayton and Humphrey cycles](image)

Figure 1.7 Pressure/volume graph of the Brayton and Humphrey cycles
Figure 1.8 Temperature/entropy graph of Brayton and Humphrey cycles

For the Brayton cycle (0-1-4-5-0 in figures 1.7 and 1.8), the efficiency is based upon the change in temperature that is experienced during the isentropic compression.

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

Eq. 1.1

The Humphrey cycle (0-1-2-3-0 in figures 1.7 and 1.8) efficiency equation has a slightly more complex form to deal with the constant volume process.

\[ \eta_{Humphrey} = 1 - \frac{T_0}{T_1} \left[ \frac{T_2}{T_1} - 1 \right]^{\frac{1}{\gamma}} \]  

\[ \frac{T_2}{T_1} - 1 \]  

Eq. 1.2
There is an additional term multiplied by the ratio of temperatures experienced in the isentropic compression. This additional term, for typical detonations is always less than one according to Bussing and Pappas [2], making the detonation cycle more efficient. Bussing and Pappas [2] also state that a 30% to 50% improvement in fuel consumption could be gained by taking advantage of this combustion process. This is especially important in hypersonic vehicles where large mass flow rates already put a strain on fuel consumption.

Another indirect benefit of the detonation process is that it naturally compresses the fuel/oxidizer mixture prior to the burning process with the Von Neumann pressure spike. Because of the self-pressurizing effect of the detonation, it reduces the need for turbomachinery or exotic compression ducts to be integrated into the flow path. This affords some weight savings as well as the potential for supersonic flow throughout the engine as is being proposed.

1.4 Thrust Augmentation with Unsteady Flow

One of the primary measures of performance for an ejector is the thrust augmentation associated with it. Thrust augmentation is defined as the ratio of thrust from the mixed flow of an ejector and a ducted inlet flow to the thrust of the ejector alone. Mathematically, thrust augmentation is expressed by the following equation.

\[ \Phi = \frac{F_2}{F_1} \]

Eq. 1.3
Figure 1.9 Illustration of thrust augmentation

As seen in Figure 1.9, the ejector flow is sometimes referred to as the primary flow, and the inlet flow, is referred to as the secondary flow.

If Eq. 1.3 is expanded, neglecting pressure effects along the walls, it takes the following form.

\[
\Phi = \frac{m_r V_r - m_s V_s}{m_p V_p} \quad \text{Eq. 1.4}
\]

For a pulsed jet in which the flow is non-steady, mass flow rates and velocities will fluctuate, negating the ability to use the equation directly.

An alternate means of determining thrust augmentation for steady-state ejectors arises in Porter and Squyers \(^3\) in which it is posed in terms of the ratio of specific heats (\(\gamma\)), and the ratio of entrainment mass flow to jet mass flow (\(\beta\)).

\[
\Phi = [1 + \beta]^{(r-1)/r} \quad \text{Eq. 1.5}
\]

The jet mass flow referred to in \(\beta\) is the same as the primary mass flow, and at rest, the entrainment mass flow can be taken to be the secondary mass flow. If this equation is applied to unsteady devices, it would still be a function of values that fluctuate according to the unsteady nature of the device, but the complexity of the problem is
greatly reduced as there are only two parameters that need to be determined: the primary mass flow and the secondary mass flow. In the experiments explored by Paxson and Wilson \cite{4}, it is found that this equation is fairly optimistic when compared to unsteady experimental data, yielding larger values than are actually seen. The disparity between actual and predicted values grows as $\beta$ is increased. The nice attribute to the equation is that it provides a rough approximation for thrust augmentation when much of the flow information is not known.

A lot of research has been done in the area of unsteady-state ejectors, and studies have found that they have more favorable thrust augmentations than steady-state devices. In fact, thrust augmentation ratios as high as 1.8 have been seen in unsteady ejectors according to Paxson and Wilson \cite{4}.

Heiser and Pratt \cite{5} discuss steady-state ejectors in supersonic flow, and some analysis has been done to use this method on unsteady-state devices as well. It is the hope of this research to find this same trend in performance for unsteady-state ejectors that have a supersonic secondary flow.
CHAPTER 2
DESIGN AND CONSTRUCTION

2.1 Experimental Design Philosophy

To test an ejector that will most accurately represent the supersonic conditions that are expected in the proposed concept, a model was made to be integrated into the supersonic blowdown tunnel at the ARC at UTA. The model would use pressure transducers and the in-house data acquisition system to gather pressure readings at crucial points in the flow. Both the pulsating equipment on the model as well as the wind tunnel control valve have to be operated remotely for safety reasons.

Because the propulsion concept being explored is expected to have some oblique compression shocks at supersonic speeds, the wind tunnel is assumed to provide this flow aft of these compression shocks indicating that a true flight speed would be greater than what the actual wind tunnel speed is.

Since both the wind tunnel and the data acquisition system have been set up previous to this study, the major components that needed to be fabricated are the model itself and the control system for the model. This fabrication took place in-house.
2.2 PDRE Model

The model for this experiment consists of a single wall-mounted pulse detonation chamber that ejects into a supersonic inlet. Aft of that is a long duct where these flows can mix. Pressure taps have been added as a means of sampling the conditions the model is experiencing at crucial locations. Figure 2.2 is a sketch of this model as it appears in the wind tunnel, and Figure 2.3 is a cutaway photo of the model after fabrication.
Overall, the PDRE is 30.0 inches long, 4.0 inches wide, and 3.125 inches tall. Cold-rolled steel was used in the construction of all major members of the model. The walls and the mounting plates were all made to be 3/8 inches thick. All parts were fastened together with screws with the exception of the supply lines to the system, which were silver brazed to the base wedge.
2.2.1. PDR Chamber

The PDR chamber itself has a 1-inch by 4-inch cross-section, and is 8.0 inches long. For measuring the flow activity within the PDR chamber four pressure taps have been made. These taps are directly along the centerline of the chamber and are spaced evenly, 2.0 inches apart from one another. The splitter plate that separates the PDR chamber from the secondary flow is tapered to a sharp point at the interface in which there is a slight expansion in the chamber flow but not the inlet flow. This taper is 30.0 degrees. To deal with the high pressures that the chamber will experience, the four plates that frame the chamber are screwed together on 1-inch centers at the joints. The rest of the model has screws every two inches.

![Fuel/Oxygen Flow for Chamber Fill](image)

Figure 2.4 Fuel and oxidizer discharging pattern in PDR
This chamber implements a front-wall injection of fuel and oxidizer from an array of cross-flow ejector ports. Fuel enters from one side, the oxidizer enters from the other, and both gases fan out into the chamber in opposite directions as a means of enhancing the mixing characteristics. There are a total of five injectors on each side that fan in 15-degree increments from the axial direction at the edges to 60.0 degrees off-axial in the center. Both the fuel and oxidizer are fed to the system via two 3/8-inch stainless steel lines. Purge air comes in the remaining ¼-inch stainless steel line in the center, and has two injectors independent of the fuel and oxidizer for it as well. These can be seen in Figure 2.4.

Figure 2.5 Purge air exhausting into the chamber
Since the purge air is only meant to be a buffer to prevent premature combustion of the incoming mixture, the mass flow rate is not critical, and that is why large injection ports and supply lines were not used.

The two remaining holes on the front wall of the chamber are to accommodate the ignition system. These holes go through the base wedge to a small trough on the outside of the engine that can be easily accessed.

2.2.2. Inlet

The engine has a straight inlet with constant area. This was done to insure that the secondary flow for high-speed testing is supersonic. Since the propulsion concept does anticipate some oblique compression shocks prior to the inlet isolator and mixing with the PDR, the wind tunnel speed represents the flow aft of these shock waves. Therefore the actual flight condition that is being tested in the supersonic runs would be at a higher Mach than that of the tunnel.

The bottom plate and the wedge base that make up the very front of the inlet have a sharp outward wedge angle of 15.6 degrees. The two side plates have a 14.2 degree outward wedge angle at the inlet. This is to ensure that oblique shocks form on the outside of the model and the inlet flow remains as close to ambient conditions as possible. The duct is 14.75 inches from the front to the mixing interface. It is 4.0 inches wide and 1.75 inches tall. Seven pressure taps were installed every 2.0 inches down the system starting 1.75 inches aft of the front of the model. This was done as a means of determining if disturbances from the PDR propagate upstream.
2.2.3. Mixing Interface

The mixing interface is a simple, constant area duct. It makes up the last 16.0 inches of the model and extends into the diffuser of the wind tunnel. It is 4.0 inches in width and 3.125 inches in height. The most significant feature of the mixing interface is the matrix of pressure taps that sit just aft of the splitter plate where the primary and secondary flow merge. This matrix was added to examine the interaction of the two flows. The matrix consists of twelve taps arranged in four rows of three and starts 1.25 inches beyond the splitter plate. The taps are spaced on 1-inch centers front to back and 0.75-inch centers top to bottom. This leaves the top and bottom taps 0.375 inches from the inner top and bottom walls of the model.

Figure 2.6 PDRE mounting plate and connecting rods

Two additional mounting plates 7.0 inches long and 11.0 inches wide were made for the top and the bottom of the model to span the width of the tunnel. At each
end of each plate are two pillow blocks that allow the model to mount on four rods in the test section. Early model integration discovered a problem with this mounting system. Due to the weight of the back of the model, a torque was induced on the rods causing the entire model to have an angle of attack of approximately 2.0 to 3.0 degrees. Since this would induce an oblique shock system inside the inlet, a propping wedge which holds the back of the model a fixed distance from the diffuser was mounted at the back of the model to hold it parallel to the flow.

2.3 Control System

The control system was designed to allow a user to open the fuel, oxidizer, and purge-air lines independently of one another and pulsate them in a constant cyclical fashion, all from the safety of the control room. Most of the actual hardware in the lab was designed to be portable for flexibility with future research at the ARC at UTA. The main components consist of a remote control box in the control room, a control cart, a rotary valve system, and an umbilical electrical cable for communication between all components and the control room.

2.3.1 Rotary Valve and Motor Assembly

Pulsating the flow for this experiment was done with a rotary valve driven by an electric motor. This entire assembly was fixed to the bottom of the supersonic wind tunnel keeping the cyclical flow lines downstream of the valve as short as possible so the time delays of the pulsing air would be kept to a minimum.
Figure 2.7 Rotary valve system installed under the wind tunnel

The rotary valve itself is a 1.5-inch shaft with 19/64-inch holes drilled through the axis. This shaft spins on bearings at each end to reduce wear and friction on the system. When these holes rotate into phase, they line up with equal diameter holes in the casing allowing the gas to pass. As the holes rotate out of phase, they break the path of the flow, which, in turn, closes the valve. The valve, due to symmetry, opens and closes twice per revolution of the shaft making the pulsating gas frequency exactly twice that of the rotary valve. The rotary valve was originally designed for another PDR experiment as a creative sidewall injection system with accommodations for six
supply lines. For this experiment, the valve was adapted to only use three of these lines, one for fuel, one for oxidizer, and one for purge air. Since purge air is needed to provide a buffer between detonations, the holes on the rotary valve are drilled 90 degrees out of phase, equating to a purge air pulse that is 180 degrees out of phase with the primary fuel and oxidizer pulse.

Figure 2.8 Exploded rotary valve assembly

The rotary valve is driven by a 1/2 hp electric motor via a timing belt. Both the rotary valve and the motor have teeth to prevent slipping. The mounting bracket for the motor has slots that allow it to translate up or down to regulate the amount of tension in
the timing belt. The motor has also been retrofitted with a variable resistor controller that allows the motor to be set at different speeds.

Figure 2.9 Motor preset controls

This was the way pulse frequency was varied in the experiments. Because this resistor was mounted directly to the motor, motor frequency, and, ultimately PDR frequency, could not be adjusted remotely. These presets all had to be set prior to the experiments. Due to the fact that this was simply an analog dial control, pulse frequency could not be set to an exact, reproducible value each time. Fortunately, the frequency of the system can be retrieved from the data being received from the data acquisition system to an accuracy on the order of the sampling rate.
2.3.2 Control Cart

As stated earlier, most of the PDR controlling devices were mounted on a portable cart. This allows future experiments to use this same control system. The primary functions of the control cart are to open and close valves for the fuel, oxygen, and purge air and drive the control motor mentioned in section 2.3.1 at the appropriate times.

Due to the fact that highly combustible gases were regulated with the control cart, pneumatic valves that were driven with shop air were used in the main supply path.

Figure 2.10 Pneumatic valves on control cart
The pneumatic valves used were manufactured by Hoke® and designed to service a $\frac{1}{2}$ inch supply line. Three of these valves were needed for the fuel (marked “propane” in figure), oxidizer (marked “Oxygen” in figure), and purge air. Flow meters were also installed on the fuel and oxidizer lines for later research. For robustness as well as anticipation for future experiments that require large mass flows, $\frac{1}{2}$ inch stainless steel piping and hardware were used to route the flow in front and aft of the valve itself. Four feet of flexible $\frac{1}{2}$ inch line by Swagelock®, also seen in figure 2.7 and 2.10, was used to connect the cart to the supply sources and the rotary valve assembly under the wind tunnel.

For the shop air that drives the pneumatics, a $\frac{1}{4}$ inch copper supply line ties the pneumatic valves to the solenoid valves on the opposite side of the cart. This allows all of the electrical systems to be as isolated from the flammable gases as possible.

![Solenoid valves on control cart](image)

Figure 2.11 Solenoid valves on control cart
Also on the opposite side of the cart is the power supply for the solenoid valves. It has a few manual controls for operating the valves at the top and fuses for each of the individual solenoid circuits.

![Solenoid Power Supply](image)

Figure 2.12 Solenoid power supply

The only other component on the control cart is the electrical relay that turns the control motor on and off. All of the circuits for the solenoids and the motor tie into a seven-prong female connector.
Figure 2.13 Seven prong female connector for control cable

This connector mates with a cable that goes to the control room and ties in with the remote control interface. Both the cable and the connections were custom made in house for this experiment.
2.3.3 Control Interface

The control interface allows the user to operate the control cart from the control room. The primary component is a switch box mounted in one of the cabinets.
This switch box allows the user to operate all of the control cart functions. There is a master power switch on the far left through which all circuits have been routed. This allows for a quick shutdown of all systems in the event of an emergency. The additional switches on the right control all of the individual functions for the cart. Lights have been provided as an indicator as to what devices are being used at all times.

2.4 Wind Tunnel

The wind tunnel used is a sub-scale supersonic blowdown tunnel that has been integrated into the ARC at UTA. This tunnel has a range of Mach 1.5 to 4 and a run time of at least 2 seconds according to Matsumoto [6]. The wind tunnel is designed to run aeropropulsion experiments which make it ideal for this series of tests.
The tunnel itself is fairly straightforward. There is a storage tube that extends out the front, followed by both a manual safety valve and a computer controlled pneumatic driver valve. Beyond the valves is a plenum chamber that is meant to condition the flow and eliminate any minor fluctuations that may be experienced. After that, the flow enters an adjustable converging-diverging (CD) nozzle that can accelerate the flow through the sonic point to the desired test section Mach number. The test section sits just aft of this, followed by a long diffuser. The test section is 0.15 meters by 0.15 meters, and the model, as mentioned, was designed around this constraint. The

![Diagram of supersonic wind tunnel](image)

Figure 2.16 Schematic of supersonic wind tunnel
test section can also be unbolted from the nozzle and slid back for access to models and test equipment.

The wind-tunnel has a separate, lower-frequency data acquisition system to monitor pressure in the storage tube, plenum chamber, and test chamber as well as temperature in the plenum chamber. The only control mechanism on the wind tunnel is the automatic valve. Both the valve control and data acquisition were done from a single computer in the control room. Matsumoto [8] details the computer code that is used to drive the valve for uniform flow during tests.

![Picture of supersonic wind tunnel](image)

Figure 2.17 Picture of supersonic wind tunnel
2.5 Modifications for Cold Flow

Due to the fact that this set of experiments are all cold flow simulations in which the gas is not to be detonated, a few modifications needed to be made to the experiment.

As stated earlier, the fuel and oxidizer supplies were replaced with atmospheric air for safety. Since provision for separate fuel, oxidizer, and purge air supplies was designed into the model and control cart for future experiments, all three lines were tied into a common ½ inch shop-air supply upstream of the control cart.

![Figure 2.18 Splice into the shop-air supply](image)

The PDRE chamber will not have any detonation to drive the flow supersonic in a cyclical manner. The only mechanism to do this in a cold flow is pressure. If the flow is to exit the chamber supersonically, there needs to be a CD nozzle at the mixing interface. A wedge was made to fit at the opening of the PDR chamber to do this. To
ensure that there is sonic choked flow at the throat, the cross-sectional area at the throat must be smaller than the entire flow path upstream. There are several places where the area of the flow path reduced, but the point of smallest diameter was the single ½ inch shop air supply line into which the three system lines splice. After the inner diameter of the pipe was measured and some simple calculations were done, it was determined that the throat for the PDR chamber would have to be smaller than 0.11 square inches. Because the model is a fixed width of 4.0 inches, the height of the throat must be 0.025 inches. The slope on the diverging part of the wedge was maintained at 15.0 degrees. There was some concern that the shallow diverging angle would blanket out the first pressure transducer tap on the model at the top of the mixing interface since a large majority of its surface is covered by the wedge, but a few preliminary tests verified that it could still be used.

Figure 2.19 Model retrofitted with a CD nozzle

In addition to this, the ports for the ignition system on the model had to be plugged as well in order to ensure that the entire flow in the PDR chamber exited through the nozzle into the mixing interface.
The rotary valve was also modified to allow the purge air line to open in phase with the fuel and oxidizer lines instead of 90 degrees out of phase. This was done as a means of increasing the mass flow per cycle and to eliminate any minor secondary pulses that might complicate the flow interpretation.

2.6 Data Acquisition System

Data was acquired with a DSP Technology, Inc. model 9200 12-bit data acquisition system. The unit is completely modular, allowing digitizing, amplifying, and storage units to be easily configured.

For the purposes of this experiment, two Model No. 2812 100 kHz 8-Channel digitizer modules were used in conjunction with the Model No. 5204 512k sample memory module. The data acquisition system was used at two different settings for the experiments. One setting provided data at a 1000 samples/sec rate, and the second setting provided data at a 2000 samples/sec rate.

2.7 Pressure Transducers

To measure pressure in the model at the tap locations, PCB model 111A24 pressure transducers were used. These transducers have a pressure magnitude range of 1000 psi at a 5 mV/psi sensitivity. The signal rise time for this model of transducer is 1μsec. Meyers [7] has shown that these transducers are adequate for capturing the magnitude and dynamics of actual detonations in PDR systems, so the cold flows here should be no problem.
Due to the short supply of transducers available, multiple runs were made at a single test condition so the available transducers could be moved to different taps on the model. The unused taps were plugged during the experiment so flow would not escape.

2.8 Data Filtering

The data acquisition system outputs raw data in the form of “counts,” which are discrete dimensionless units. Because it is a 12-bit system, there are $2^{12} = 4096$ counts that represent the range of possible values. In order to convert these counts into meaningful data such as “psig,” a scaling factor must be applied as well as an offset value. When this information is gathered immediately after an experiment, it tends to be filled with some erroneous high frequency noise that must be eliminated to see the true trend in the data.

The signal processing toolbox in MATLAB®, version 7.0 was used to eliminate this noise. Prior to applying the scaling factor and offset, the raw “counts” data were imported directly into MATLAB® and a low-pass filter was then used to condition it. It was then exported as a single column of values to an Excel file where the data could be converted to “psig.” Since time information was not provided to MATLAB®, the independent variable assumed by the signal processing toolbox is the number of the data value in the column.
CHAPTER 3
DATA COLLECTION AND OBSERVATIONS

3.1 Runs Conducted

Because the tests are interested in seeing if this mode can accelerate from rest to supersonic conditions, it was important to perform a set of runs at each of these conditions. Also, it was important to see what effect varying the frequency of the PDR cycle would do to performance. With these conditions to explore, a system of five runs was conducted.

The first run was a steady-state static test. In this test, the PDR ejected into the mixing interface in a constant, non-cyclical fashion. The motor driving the pulsating flow was turned off and the test section was unbolted from the nozzle and detached to allow the engine to breathe properly while the wind tunnel was off. This was to give a steady-state ejector baseline for our system to gauge the performance of the pulsating flows.

The second and third tests were a low and high frequency repeat of the first, respectively. The wind tunnel remained off, and the motor was set to drive the PDR to an arbitrarily low and high pulsing frequency. This was done as a means of determining the effect of frequency on performance.
The last two tests were low and high frequency tests of the model at supersonic conditions. The motor was varied in the same manner as before, but in these tests, the wind tunnel was used to simulate supersonic flight.

Since there are a great number of pressure transducer locations that will be examined in all tests, a shorthand naming convention has been provided to indicate specific locations. This is especially important in the pressure plots that are to follow.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDR1</td>
<td>Forward-most position in PDR chamber</td>
</tr>
<tr>
<td>PDR2</td>
<td>Second position in PDR chamber from front to back</td>
</tr>
<tr>
<td>PDR3</td>
<td>Third position in PDR camber from front to back</td>
</tr>
<tr>
<td>PDR4</td>
<td>Aft-most position in PDR chamber</td>
</tr>
<tr>
<td>INLET1</td>
<td>Forward-most position in inlet</td>
</tr>
<tr>
<td>INLET2</td>
<td>Second position in inlet from front to back</td>
</tr>
<tr>
<td>INLET3</td>
<td>Third position in inlet from front to back</td>
</tr>
<tr>
<td>INLET4</td>
<td>Fourth position in inlet from front to back</td>
</tr>
<tr>
<td>INLET5</td>
<td>Fifth position in inlet from front to back</td>
</tr>
<tr>
<td>INLET6</td>
<td>Aft-most position in inlet</td>
</tr>
<tr>
<td>BOTTOM1</td>
<td>Forward-most position in mixing interface on bottom-most row (aft of secondary flow)</td>
</tr>
<tr>
<td>BOTTOM2</td>
<td>Second position in mixing interface from front to back on bottom-most row (aft of secondary flow)</td>
</tr>
<tr>
<td>BOTTOM3</td>
<td>Aft-most position in mixing interface on bottom-most row (aft of secondary flow)</td>
</tr>
<tr>
<td>NBOTTOM1</td>
<td>Forward-most position in mixing interface on second row (aft of secondary flow)</td>
</tr>
<tr>
<td>NBOTTOM2</td>
<td>Second position in mixing interface from front to back on second row (aft of secondary flow)</td>
</tr>
<tr>
<td>NBOTTOM3</td>
<td>Aft-most position in mixing interface on second row (aft of secondary flow)</td>
</tr>
<tr>
<td>NTOP1</td>
<td>Forward-most position in mixing interface on third row (aft of primary flow)</td>
</tr>
<tr>
<td>NTOP2</td>
<td>Second position in mixing interface from front to back on third row (aft of primary flow)</td>
</tr>
<tr>
<td>NTOP3</td>
<td>Aft-most position in mixing interface on third row (aft of primary flow)</td>
</tr>
<tr>
<td>TOP1</td>
<td>Forward-most position in mixing interface on top row (aft of primary flow)</td>
</tr>
<tr>
<td>TOP2</td>
<td>Second position in mixing interface from front to back on top row (aft of primary flow)</td>
</tr>
<tr>
<td>TOP3</td>
<td>Aft-most position in mixing interface on top row (aft of primary flow)</td>
</tr>
</tbody>
</table>
After the data was filtered and converted to “psig,” it was converted to a pressure ratio using an ambient pressure reading from a barometer the day of the experiment. The convenience of manipulating the data in this fashion will be seen as the analysis is conducted.

\[
\frac{p_{\text{static}}}{p_{\text{amb}}} = \frac{p_{\text{run}}}{p_{\text{amb}}} + \frac{p_{\text{amb}}}{p_{\text{amb}}}
\]

\text{Eq. 3.1}

3.2 Mach 0 Steady-state Run

For the steady-state run, the data acquisition system was set to sample pressure readings at 1000 samples/sec. This was the case for all Mach 0 tests. It was also turned on prior to the activation of the control motor so as to capture the total response of the system to the step input from the ejector. A total of 5.12 seconds of run time was collected, but after filtering, only 4.32 seconds of run time was valid.

This test was not only important for providing a baseline for the pulsing ejector tests, but also was intended to verify that the CD nozzle built for the cold flow was designed correctly to provide supersonic flow at the entrance to the mixing interface.
From the data gathered in the PDR, the transducers show that the system has a slightly under-damped second-order response to the motor activation. Once the transient response has decayed, the averaged pressure ratio from the last three transducers of 2.18 remains. The first was not used because of the lack of correlation to the other three as will be discussed later. Because the chamber to throat area ratio is 40.0, it can be assumed that the static pressure readings inside the chamber are close to stagnation values. This claim is validated by the fact that all transducers experience a pressure rise simultaneously when the flow is initiated. Even though the transducers do not agree on a final value, this uniform reaction suggests that the PDR chamber is acting more like a storage tank than an open-ended duct.

On the diverging section of the nozzle, the final area ratio \( (A/A^*) \) at the perpendicular plane of the splitter plate is 22.96. Mattingly\(^8\) shows that for expansion ratios on this order, there is a sonic condition at the throat for nozzle pressure ratios (NPR), \( p_{\text{chamber}}/p_{\text{ambient}} \) only slightly greater than 1.0. Unfortunately, this text also
indicates that there are shocks that form inside the nozzle slowing the flow to subsonic conditions for an NPR less than 14.0. This is a rather large expansion for such a low pressure ratio driving the flow, and it is anticipated that, because of this, the flow is highly over-expanded. The flow experiences a shock somewhere in the nozzle to recompress it back to the exhaust pressure. Unfortunately, this indicates that the rest of the experiment aft of this location is subsonic as the cross-sectional area continues to grow.

One point of contention is the data provided from the first transducer. It drifts to much lower values with respect to time after the PDR is started. The most likely explanation is that the first pressure transducer is experiencing “transducer drift” in which temperature sensitivities play a factor. Since all the transducers measure electrical resistance, a change in temperature can affect the voltage that the transducer sends to the data acquisition system. Since it is the first transducer in the flow where the air is expanding from a higher pressure in the supply lines, it might feel the drastic effects of the natural cooling from the air coming into the system from the injectors at the front of the chamber. This effect, seen primarily in the PDR chamber in the Mach 0 tests, is greatly amplified in the supersonic runs as will be seen later.

To look at the primary mass flow, the mass flow equation must be applied to a point in the primary stream where the flow conditions are known. The obvious choice is the throat of the CD nozzle. Even though the flow conditions are not known at this point, it is assumed that the flow is choked at this location and flow properties can
easily be determined from upstream flow properties. Recall the following equations for determining mass flow and speed.

\[ m = \rho VA \] \hspace{2cm} \text{Eq. 3.2}

\[ V = M \sqrt{\gamma RT} \] \hspace{2cm} \text{Eq. 3.3}

Unfortunately, the flow properties at the throat are not known, so an alternate form of extracting this information is needed that relates the mass flow at this point to flow properties upstream. The mass flow parameter (MFP) as seen in Mattingly \cite{8} does that by relating the mass flow at a given Mach number to total pressure and total temperature.

\[ MFP(M) = \frac{\dot{m} \sqrt{T_t}}{P_t A} = \frac{M \sqrt{\gamma/R}}{\left\{1 + [(\gamma - 1)/2]M^2\right\}^{(\gamma+1)/[2(\gamma-1)]}} \] \hspace{2cm} \text{Eq. 3.4}

For sonic conditions, if \( \gamma \) is assumed to be 1.4 and \( R \) is assumed to be 287 J/kg-K, the MFP is equal to 0.04042. The assumption has already been made that the pressure in the PDR chamber can be approximated as the total pressure, which means the last parameter to determine is the total temperature. If it is assumed to be at room temperature, a thermometer reading from the day of the experiment indicates that this should be a value of 293.15 K (68°F). The cross-sectional area for the throat is 0.1 square inches (0.025 inches by 4.00 inches) or 6.45*10^{-5} square meters.

With all of that information known, the mass flow for the PDR is 0.032 kg/sec.
Figure 3.2 Mach 0 steady-state inlet pressure readings

In looking at the data for the transducer readings in the inlet, the majority experience a slight drop in pressure ratio, once the ejector is started, to an average value of 0.995. Due to the fact that the inlet is exposed to the ambient air in the room, the ambient pressure is also the stagnation pressure for these transducers. The drop in pressure indicates that some of the total pressure is converted to dynamic pressure. This means that the ejector is entraining air as it was designed to do. Referring again to the compressible isentropic flow equations, a pressure ratio of 0.995 indicates that the flow in the inlet is at Mach 0.085.

There is also a relatively large transient response to the ejector start by the transducer in the most aft position in the inlet, but this effect does not propagate any further upstream.

To look at the entrainment mass flow, the same equation is applied using the flow properties of the ambient air in the room. The cross-sectional area for the inlet is 7.0 square inches (4.0 inches by 1.75 inches) or 0.00452 square meters. If the air is
assumed to have a temperature of 293.15 K (68°F) as stated earlier and a ratio of specific heats of 1.4, the mass flow for the inlet is 0.152 kg/sec.

Figure 3.3 Mach 0 steady-state mixing interface pressure readings (bottom)

Coming into the mixing interface, the flow from the inlet initially does not vary significantly. The first transducer on the bottom row settles on a pressure ratio of about 0.995, just like the average reading from the inlet transducers. For the row just above that, the first transducer indicates that the pressure ratio is 0.986 after transient effects have decayed. If total pressure from the ambient air is assumed to remain unchanged by mixing with the much higher primary jet, this indicates that the flow at this location is
moving at a slightly higher velocity. When flow tables are consulted, the flow is at Mach 0.145 under this assumption. The second and third transducers in both rows show a rise in pressure above ambient conditions. This rise in pressure is a realization of energy being imparted to the secondary flow from the ejector. It is not known exactly how much stagnation pressure is gained by the secondary flow, and this precludes making a prediction in velocity. Kerrebrock [9] made some estimates of how much stagnation pressure is gained in a mixing chamber, but these estimations can only be made far downstream where the flow properties are homogenous throughout the system. Based upon the static pressure plots, it would not be valid to make this assumption at this location. The model further assumes constant cross-sectional area which the presence of the CD nozzle insert invalidates.
Figure 3.4 Mach 0 steady-state mixing interface pressure readings (top)

The transducers at the top of the mixing interface experience the most radical pressure ratios external to the PDR chamber.

As stated earlier, it was not certain that the first transducer on the top row would be blanketed out by the CD nozzle insert, but according to the data gathered here, the data it produces are consistent with the rest of the system. It shows a large pressure ratio drop to a value of approximately 0.87 after the ejector is started. This reading agrees quite well with the fact that it is the transducer location that is closest to the nozzle throat where flow speed is still quite large. As the flow continues down stream, the flow velocity continually reduces, as is verified by the second and third transducer at the top
of the mixing interface. Notice that each transducer shows less of a decay in pressure ratio when the system is started than the transducer before it. This trend validates the fact that the flow is indeed subsonic as previously thought. If it were supersonic, the flow would undergo a progressive decrease in pressure as it continued to expand to higher Mach numbers.

As for the row of transducers below that, a similar, but less drastic trend is seen. The first transducer sees the greatest drop in pressure with the last transducer seeing the least. Again, this validates that the flow is subsonic. Since the primary flow has a greater total pressure than the secondary flow, it can be inferred that the velocity in this row of transducers is greater than the row below.

Unfortunately, due to the presence of a shock wave in the system, as validated by the pressure readings in the upper portion of the mixing interface, it cannot be assumed that the stagnation pressure in the flow path of the primary flow is equivalent to what is in the PDR chamber. The stagnation pressure ratio \( \frac{p_{s1}}{p_{s2}} \) can be bounded to a value that is less than 2.2 due to shock losses, and greater than 1.01 due to the highest reading in the mixing interface. Because this is not known, a true assessment of the velocity can not be made as was the case in the lower portion of the mixing interface. Only a prediction of the trend based upon knowledge of compressible flow theory can be made.
Figure 3.5 Estimated velocity vector field of steady-state run

Understanding that total pressure would be higher at the top of the mixing interface than below the splitter plate coupled with the transducer readings, it is reasonable to guess that the flow velocity at the aft end of the mixing interface decays from top to bottom. Even though the bottom is the point of lowest velocity, it is assumed that the flow speed is slightly greater than that of the inlet as the primary flow accelerates it across the shear layer. Since pressure readings confirm that the system is subsonic in the mixing interface, a shock system as seen in fig. 3.5 is anticipated. Since the area expansion is great, it is expected for the flow to detach from the walls with a shock induced flow separation. This translates into a much thicker shear layer area than would typically be seen if the flow were fully attached.

Because accurate information of velocity can not be extracted at the exit plane being examined, thrust augmentation can not be determined by conventional means.
However, from the analysis done on the PDR and the inlet, there is an entrained mass flow to primary mass flow ratio, $\beta$, of 4.682. If this value is inserted into the Porter and Squyers\textsuperscript{[3]} method for solving for thrust augmentation (Eq. 1.5), it is determined that the steady-state ejector has a thrust augmentation of 1.643.

### 3.3 Mach 0 Low Frequency Run

The low frequency run was set up just like the steady-state run in terms of the data acquisition system settings. It was set at 1000 samples/sec allowing a total post-filtered run time of 4.32 seconds. Again, pressure readings were adjusted to pressure ratios using Eq. 3.1. As previously stated, the frequency could not be put to an exact setting due to analog controls on the timing motor. The motor is set to an arbitrarily low setting, and the frequency information is extracted from the data after the run is made.

![Figure 3.6 Mach 0 low frequency PDR pressure readings](image)

A simple count of the pulses in the PDR chamber divided by the run time yields this frequency information. For this condition, the frequency is 11.1 Hz. The peak pressure
ratio at the crest of each pulse rises to a maximum value of 2.8. This peak pressure in
the PDR is almost \( \frac{1}{2} \) an atmosphere over the steady-state case. This is due to the fact
that the PDR is slightly under-damped as discovered in the steady-state run and because
the valve closing and opening at a much higher frequency does not allow the much
slower frequency response of the system time to equalize.

The temperature drift effect is again seen in the first pressure transducer
position. This time, the effect is severe enough to cause it to output negative values
which is physically impossible. This further validates that this is an instrumentation
effect and not an accurate reading.

Because there is no noticeable time lag in pressure readings from front to back,
the assumption that the flow is stagnant in the chamber is still valid. Adding a degree of
complexity to the steady-state run, the value of the stagnation pressure at the mixing
interface is made less certain by the fact that the total pressure in the PDR fluctuates
from ratio values of 0.9 to 2.8. The fact that the values decay below 1.0 indicates that
the pressure transducers for the system might be experiencing temperature effects as the
chamber cools from the reduction in pressure. If no additional flow is added to the
system between chamber fills, this value should asymptotically approach 1.0 meaning
that the value should always be some finite value greater than 1.0. Again from
Mattingly \(^8\), due to the very large expansion ratios seen in the CD nozzle, it is valid to
assume that the throat is experiencing sonic conditions for the entire cycle.

After removing the drift in the first transducer location, the remaining time
averaged pressure ratio is 1.65, much lower than the steady-state case of 2.18.
Determining a mass flow rate now becomes increasingly complex due to the fact that the pressure changes with respect to time. However, if the same assumptions are made as in the steady-state run with the exception that the total pressure changes with a function of time according to the transducer data, a reasonable value for mass flow can be extracted, again, via the mass flow parameter.

![Cyclical Mass Flow Rate](image)

Figure 3.7 Mach 0 low frequency primary flow mass flow rate

The cyclical mass flow rate for the primary flow varies as a direct function of the pressure in the PDR chamber, to peak values of approximately 0.041 kg/sec to low values of 0.015 kg/sec. A time-averaged mass flow extracted from the calculated data, taken over 3.32 seconds of steady run time indicates that the PDR is pumping at a rate of 0.024 kg/sec. This is significantly lower than the mass flow calculated for the steady-
state ejector as expected since the flow is stopped for a portion of the cycle unlike the steady-state case.

Figure 3.8 Mach 0 low frequency inlet pressure readings

For readings in the inlet, the first five transducers in the inlet as shown in figure 3.8, all see a drop in pressure ratio to an average value of 0.988 after the motor is activated. Again assuming that the ambient pressure is a good value for total pressure and using isentropic flow properties, it can be determined that the flow in the inlet is traveling at Mach 0.130. Recall that the speed predicted in the inlet for the steady-state flow was Mach 0.085. This indicates that a pulsed ejector is inducing a greater impact on the secondary flow. This translates to an entrained mass flow of 0.247 kg/s making the same assumptions on the ambient air.

Even though the transducers do respond to the pulses, this response is limited to negligible changes of the same frequency in pressure ratio with the exception of the most aft transducer. It responds to the pulses emitted from the PDR with maximum values of 1.03. This is similar to the transient effect seen in the steady-state run, but this
effect never settles with the unsteady flow. Again, this proves that these effects do not propagate upstream, and the unsteady nature on the PDR has no macroscopic effect on the secondary flow path other than inducing greater velocity, and subsequently, greater mass flow.

Figure 3.9 Mach 0 low frequency mixing interface pressure readings (bottom)

Information from the data in the lower region of the mixing interface is similar to the data gathered for the steady-state test. The first two transducers see a drop in pressure with the lower transducer agreeing well with the pressures in the inlet. It maintains an average pressure ratio value of 0.988 giving it the same Mach 0.130 flow speed as that observed with an ambient stagnation pressure value. If the stagnation
value is higher, there will be a slight acceleration over the inlet values at this location. The transducer closer to the PDR produces an average pressure ratio reading of 0.983. Isentropic flow properties dictate that this location will experience flow speeds of Mach 0.155 with the same stagnation assumption.

Upon inspection of the second and third pressure transducer locations, a similar trend to that of the steady-state run is seen. All show a steady rise in pressure due to the energy being transferred from the mass entrainment. Maximum time-averaged pressure ratios at the last transducer column are 1.015 for the bottom row and 1.024 for the row above it, which are both higher than the matching steady-state values. Again, velocity can not be determined as the actual stagnation information remains undetermined for the same reasons stated earlier.
Figure 3.10 Mach 0 low frequency mixing interface pressure readings (top)

The pressure information from the upper region of the mixing interface validates the fact that the flow is subsonic entirely aft of the nozzle as before. As the flow moves front to back, the pressure ratios get less dramatic as the flow continues through the growing cross-sectional area.

Looking at the top row, the first transducer experiences a cyclical drop in pressure to values as low as 0.84. The other two transducers, like the first, have a very steady oscillating response to the PDR flow but with a much smaller amplitude. The flow in the row below it does show responses to the pulsed jet, but these responses are noisy and less ordered like the rest of the system. This means the effects of the pulsating
flow are greatest along the upper surface of the primary flow and dissipate further down the mixing area. This suggests that a strut mounted ejector may have less transient effect on the total flow since there is no wall for the oscillations to adhere against as opposed to a wall mounted ejector.

- At maximum pulse pressure
- At minimum pulse pressure
- Insensitive to pulse pressure

Figure 3.11 Estimated velocity vector field of low frequency run

With this information, it is still difficult to predict stagnation pressures in the flow, and, in turn, velocity. From the data available, it can be said that the upper wall of the model experiences the most consistent cyclical change in pressure. Without having an accurate assessment of total pressure, it is not known how this impacts velocity. With the unsteady flow, it is expected to show "jelly rolls" in the flow, greatly expanding the shear layer in the mixing interface, and it is anticipated that the shear layer will grow
more in the direction of the secondary flow due to the average pressure ratio difference between the two flows. Similar to the steady state flow, a shock structure forms in the nozzle of the PDR and detaches it from the wall. As the PDR pulses, the shock will fluctuate making the point of separation change as a function of the cycle. This will expand and contract the primary jet between the shear layers as well.

Again if the entrainment ratio is calculated, it is determined to be 10.29. Using the same method as was used in the steady-state run, a value of 2.00 is predicted for thrust augmentation.

3.4 Mach 0 High Frequency Run

The high frequency run, once again, used the same settings for the data acquisition system as the low frequency and steady-state runs. The driving motor was set to an arbitrarily high frequency and data was sampled. For convenience, data was converted into pressure ratios once again.

![PDR Chamber](Image)

Figure 3.12 Mach 0 high frequency PDR pressure readings
In the PDR chamber, from counting pulses over a given length of time, it is determined that the PDR frequency was 22.9 Hz. Unlike the low frequency data, the pressure ratios in the chamber only climb to values of 2.3 and decay to values of 1.3. Recall that for the low frequency run, this was 2.8 and 0.9 respectively. While this still is enough pressure to ensure a sonic condition for a portion of the cycle, the resulting oscillations in the system are expected to be less intense. The reason that these pulses are less dramatic is due to the limits of the rotary valve and the PDR throat. As the valve rotates at higher speeds, there is less time that the valve is in phase. This indicates that a smaller slug of air is allowed through the valve into the system reducing the maximum pressure. Since the PDR is acting more like a storage tank than a duct due to the small throat area, the pressure capacitance of the chamber is not fully depleted before the next cycle either.

As seen in the data, the first and third pressure transducers experience transducer drift, but the high frequency response of all the transducers agree well with one another. Time averaged data from the transducers that do not show drift indicate that the average pressure ratio is 1.79, slightly higher than the low frequency run, but still much less than the steady-state run.
Figure 3.13 Mach 0 high frequency primary flow mass flow rate

For the high frequency run, taking advantage of MFP and assuming the sonic condition at the throat, the mass flow for the higher frequency run does not fluctuate as much as the low frequency mass flow, but it is consistently higher. This is due to the fact that less of the pressure capacitance drains out of the chamber prior to the next fill as was reflected in the comments about the pressure readings. The values oscillated between 0.021 kg/sec and 0.034 kg/sec. The time averaged value for mass flow is 0.027 kg/sec taken over 3.32 seconds of steady run time.
Figure 3.14 Mach 0 high frequency inlet pressure readings

Unfortunately, the pressure readings from the inlet do not agree as well as in the low frequency test. In fact, the first, fourth, and fifth transducer see no net effect before and after the ejector is started. If an average of all transducers is taken, a pressure ratio of 0.995 is seen. This is identical to the steady-state run, indicating that the flow is Mach 0.085 under the standard assumptions. Since that is the case, it yields the same value for entrained mass flow of 0.152 kg/sec.

One unique effect in the inlet is that there is no cyclical transient response from the last transducer as seen in the low frequency test. The transient effect is more like the steady-state run in which there is a relatively large pressure gain upon initiation of the PDR that dampens out as the system continues to run.

All the transducers show a high frequency response to the PDR, but the pressure ratios associated with it are negligible, being noisy and non-cyclical. This same effect was seen in the low frequency runs and was discounted for the same reason.
This data suggests that the high frequency run behaves more closely to the steady-state system than it does the unsteady device. This may be that the cycle frequencies are too fast for the system to respond to them coupled with the fact that the pulse pressure amplitudes are smaller.

Figure 3.15 Mach 0 high frequency mixing interface pressure readings (bottom)

Coming into the mixing interface, the same trends in the steady-state and low frequency tests are apparent. The first transducer on the bottom row settles on a pressure ratio of about 0.995 and the first transducer on the row above indicates that the pressure ratio is 0.985 at that location. Again, this is very similar to the values seen in the steady-state run. If the assumption of total pressure for the first two transducers is
maintained, the average flow speed is Mach 0.085 at the lower transducer and Mach 0.145 for the upper transducer.

The pressure gains in the second and third columns, however, are more consistent with the low frequency ejectors. The bottom row climbs to averaged pressure ratios on the order of 1.015, and the row above it sees an increase to 1.023 after transient effects have decayed. As before, velocity remains undetermined at these locations.

Figure 3.16 Mach 0 high frequency mixing interface pressure readings (top)

For the top row, the transducers again see the most ordered response to the flow. The values for the first transducer location are somewhat attenuated due to the lower amplitude in the PDR chamber only reaching pressure ratios of 0.885. The transducers
again validate the fact that the flow is subsonic in the presence of a growing cross-sectional area.

The row below it shows a small pressure drop upon initiation of the PDR. All values seem to decay only slightly to 0.998. It is assumed that the loss in dynamic pressure for these transducers is almost exactly offset by the gain in total pressure, resulting in almost no net change in static pressure.

Considering all of the data presented, the high frequency run is more of a hybrid of the steady-state and low frequency runs, containing distinct elements from both. The induced effects on the secondary flow are very close to the steady-state run, but the large velocity gradients along the upper wall of the model are more consistent with the low frequency fluctuations. It is safe to say that if the net effect on the secondary flow of the higher frequency PDRE pulses is roughly equivalent to that of the steady-state ejector, the pulsed jet remains more efficient. This is by virtue of the fact that the primary flow in the pulsed jet has a much smaller average mass flow due to the periodic starting and stopping of the flow.

Using Porter and Squyers [3], the \( \beta \) term is calculated to be 5.63. When applying that to Eq.1.5, a thrust augmentation of 1.72 is calculated.

3.5 Supersonic Runs

For the supersonic runs, the data acquisition system was set to collect pressure readings at 2000 samples/sec. The data was filtered in the same manner as the
Mach 0 cases in which all the pressure data was normalized with respect to ambient pressure.

For these runs, the data acquisition system was turned on prior to the activation of the motor and the wind tunnel so there would be a portion of data at the beginning of the run that indicates stagnant conditions of the system. The run time of the system was increased to 10.24 seconds to allow plenty of time for the wind tunnel to ramp up to supersonic conditions and capture the entire supersonic portion of the data. Like the Mach 0 cases, once the data was filtered and manipulated, only 4.5 seconds was extracted for further examination.

![Wind Tunnel Pressure Readings](image)

**Figure 3.17** Supersonic wind tunnel pressure readings for low frequency runs

Since the wind tunnel was activated, the data was also gathered from specific places on it as well. Recall that multiple runs had to be done at each design
condition due to the lack of pressure transducers and limitations on the data acquisition system. That is why two sets of data are presented in Figure 3.17. The strong correlation between the two graphs indicates that the wind tunnel has high repeatability in its results. Note that the plot labeled “P total in test section” is not a true total pressure. It is a “cabin pressure” used for calibrating the wind tunnel prior to setup.

Looking at the static pressure data in the test section, there are two large pressure jumps in both runs. These pressure jumps are associated with the acceleration through Mach 1 and deceleration through Mach 1 back down to subsonic speeds. This frames the supersonic portion of the flow nicely for analysis.

Much like the frequency of the control motor, the true Mach condition of the flow can only be backed out from the data after the run. If the velocity in the plenum chamber is assumed to be slow enough to represent stagnation conditions, the pressure ratio \( p/p_e \) in the test section is approximately 0.090. Isentropic flow properties reveal that the actual speed of the tunnel in the test section is Mach 2.23.

![Figure 3.18 Supersonic low frequency PDR pressure readings](image)

---

65
The pressure transducers in the PDR chamber showed similar results to the data from the low frequency runs as expected. Once again, counting the pulses over time indicates that the run operated at a 13.6 Hz rate. Despite experiencing some transducer drift on the first, second, and third locations, the only problem in the data is some erroneous excitations in the third transducer between 3.2 and 4.0 seconds. It is anticipated that this is due to the fact that the transducer was not tightened down enough and some minor vibrations caused it to jump as the tunnel decelerated past Mach 1.

Mass flow is calculated in the same manner as was done in the Mach 0 tests, and a total primary mass flow of 0.024 kg/sec was obtained.

![Figure 3.19 Supersonic low frequency inlet pressure readings](image)

In the inlet, the data becomes increasingly difficult to interpret. Three of the transducers (third, fifth, and sixth) upon initiation of the wind tunnel drop in pressure and then rise to some saturated value where they stay for the remainder of the run. The data is clearly erroneous, but there has been no reasonable explanation for this behavior. The fact that they endure no fluctuation as they saturate indicates the possibility of
transducer failure. Careful documentation during the test, as will be seen later indicates that the problem is unique to the transducer and re-appears in the mixing interface information as well. The first transducer experiences some excitation, but the reason for this may be similar to the third transducer in the inlet in which the supersonic flow vibrated it loose inside its pressure tap. This hypothesis is supported by the fact that the oscillations are minimal at first and escalate throughout the supersonic portion of the test.

The remaining two transducers are the only ones in the inlet from which meaningful data can be extracted. Both show a steady rise upon the acceleration of the wind tunnel, but then show an almost linear decay until the wind tunnel deceleration in the test. This linear decay, even though different for the two transducers, is the most well behaved example of transducer drift seen. It becomes obvious when considering the flow properties of the wind tunnel. Isentropic flow properties state that the wind tunnel experiences a temperature ratio \( T/T_i \) of 0.508 for the associated pressure drop. Temperature readings in the plenum chamber indicate that the flow is at 67° F or 19.4° C (292.6 K). That would indicate that the flow in the test section is at -192.1° F or -124.5° C (148.6 K) which is well below the specification ratings for these transducers. Essentially the transducers are being super-cooled as a result and the pressure readings reflect that dipping into negative pressure ratios. The transducers have a temperature sensitivity of 0.36%/° C. Given the entire range of the temperature drop, this equates to a 51.84% degradation in signal from the transducer.
An approximation of the effect can be made by looking at the properties of the transducers. The total range of the transducers is ±249.85 psig or a total of 499.70 psig. If that is the case, a 51.84% reduction in signal would attenuate that to a total range of 259.04 psig. The attenuated signal must be expanded from the absolute lowest reading, although physically impossible, across the entire original range in the following manner.

\[
P_{\text{actual}} = \frac{(P_{\text{reading}} - P_{\text{min}})}{w_{\text{trans}} \Delta T} \cdot \frac{R_{\text{total}}}{2}
\]

Eq. 3.5

For a total pressure range of 499.7 psig, a minimum pressure reading of -249.85 psig, and the given sensitivity, the following transducer map can be constructed correlating pressure readings and temperature effects.

![Temperature Effect on Transducers](image)

Figure 3.20 Dilation of pressure results due to temperature
The important thing to note is there are no major departures from this near-linear decay during the steady-state run time of the tunnel. That indicates that the flow is traveling though the inlet at a constant supersonic rate with no propagations up or downstream.

If in fact the inlet is experiencing the same Mach number as the wind tunnel, a calculation of mass flow can be done using the MFP. Bear in mind that the total pressure and total temperature are no longer ambient conditions, but the conditions inside the plenum chamber. With that indicated, the mass flow for the inlet is 4.36 kg/sec.

Figure 3.21 Supersonic low frequency mixing interface pressure readings (bottom)
The same behavior is also seen in the transducers in the lower region of the mixing interface. A small pressure rise at the beginning of the test occurs followed by a steady decay. In addition to the fact that the data agrees well with the useable data in the inlet, the second row of transducers shows more of a decay in pressure readings than the first. This might indicate that on average, the flow at this location is colder. If this is the case, this means that the flow is accelerating, at least faster than the bottom row. This trend is apparent parallel to the flow as well with the first transducer in each row decaying at a slower rate.

This indicates that an isentropic expansion is bending the secondary flow into the primary flow. This explanation also agrees with [Kerrebrock\textsuperscript{[9]}] in which the total pressure ratios ($p_{\text{secondary}}/p_{\text{primary}}$) is approximately 8.
Figure 3.22 Supersonic low frequency mixing interface pressure readings (top)

In the upper region of the wind tunnel the same transducers that increased to saturation limits in the inlet cause the same problems here. That essentially means the transducers from the front and last position on the top row and the first transducer in the row just below that are the only ones that can be trusted. The first in the top row is the only location outside the PDR that indicates the presence of a pulsed flow. It further does not drift, indicating that the flow in this region is entirely from the primary flow. The remaining two transducers see a minimal transducer drift indicating that the two flows are mixing at these locations.
Figure 3.23 Estimated velocity vector field of supersonic runs

Upon inspection of the high frequency run at supersonic conditions, there was virtually no change in the data with the exception that the first transducer in the top row of the mixing interface sees a higher frequency pressure fluctuation. This is due to the fact that the difference in mass flow from the primary to the secondary is so high that the effects of the PDR are diminished greatly. Results from the high frequency test are included in Appendix B and in Table 4.1 for reference.

With that in mind, it is anticipated that the secondary flow actually expands in a near-isentropic nature into the primary flow. The expansion fan is reflected off the lower surface of the model to turn the flow back into the axial direction. Because of transducer drift and a lack of total pressure information, it is hard to determine the
magnitude and impact of this expansion on the system. It is also anticipated that this expansion/shock structure extends far past the last column of transducers. There is a shear layer in the system. This is seen in some of the transducer readings in the upper portion of the mixing interface where there is a temperature drift effect, but not as great as the transducers that were located completely in the secondary flow.

Unfortunately, due to the fact that the flow is moving relative to the inlet, it cannot be assumed that the air flowing through it is entrained mass. Further, this negates the ability to use the Porter and Squyers\textsuperscript{[3]} method for determining thrust augmentation.
CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Results from Tests

All Mach 0 tests indicate that unsteady ejector performance is better than steady performance as was expected [Paxson and Wilson $^{[4]}$]. Quantifiable results for thrust augmentation were obtained via the Porter and Squyers $^{[3]}$ method, but proved to be slightly too optimistic to be trusted. As stated earlier, 1.8 is the highest value that has been recorded for unsteady ejectors according to Paxson and Wilson $^{[4]}$ where the low frequency run predicts a value of 2.00. A more accurate prediction of thrust augmentation could not be used due to the lack of knowledge of total pressure in the mixing interface, but it was determined that the secondary flow is relatively insensitive to the primary flow fluctuations, and higher frequency ejector rates drive the system to results closer to steady-state.

As for supersonic test results, there was little to no effect on the secondary flow from the primary flow due to the large mass flow ratio between the secondary flow and the primary flow. It is anticipated that this will be one of the limiting factors on what speed mode 1 of the propulsion concept [Munipalli et al. $^{[1]}$] will be able to attain as the primary flow will be fixed as the secondary flow will be able to change drastically.

Despite the issues with inaccurate mass flows, this set of runs gives a picture as to what an actual detonating PDRE will produce during some benign part of the cycle
such as the purge air fill. The system can also be viewed in reverse, and provide insight into what a detonation flow would do in a slow subsonic condition. If the secondary flow was the primary and vice versa, this sort of trend is expected as a high-pressure detonation expands into a slow-moving flow. The major difference would be the lack of temperature effects since that phenomenon would be associated with a very hot gas.

It is also important to note that, the inlet did truly experience supersonic flow throughout its length with no perturbations propagating upstream.

<table>
<thead>
<tr>
<th>Run</th>
<th>Frequency</th>
<th>Primary Mass Flow</th>
<th>Secondary Mach</th>
<th>Secondary mass flow</th>
<th>(\beta)</th>
<th>(\Phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach 0 Steady-state</td>
<td>0.0</td>
<td>0.032</td>
<td>NA</td>
<td>0.085</td>
<td>0.152</td>
<td>NA</td>
</tr>
<tr>
<td>Mach 0 Low Freq.</td>
<td>11.1</td>
<td>0.024</td>
<td>0.130</td>
<td>0.247</td>
<td>10.29</td>
<td>2.00</td>
</tr>
<tr>
<td>Mach 0 High Freq.</td>
<td>22.9</td>
<td>0.027</td>
<td>0.085</td>
<td>0.152</td>
<td>5.63</td>
<td>1.72</td>
</tr>
<tr>
<td>Supersonic Low Freq.</td>
<td>13.6</td>
<td>0.024</td>
<td>2.23</td>
<td>4.36</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Supersonic High Freq.</td>
<td>28.6</td>
<td>0.027</td>
<td>2.23</td>
<td>4.36</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

4.2 Recommendations for Future Work

There were several major pitfalls in this set of experiments that need to be addressed.

The lack of total pressure information at the last column of pressure transducers precluded the calculation of thrust augmentation in this set of runs. It is recommended to integrate a stagnation pressure rake inside the model as a means of sampling the
variation from top to bottom of this parameter. With that information as well as static pressure known, dynamic pressures can easily be extracted to determine what the true velocity is. In the same vein, it would be beneficial to make provisions for a static and stagnation tap at the aft end of the mixing duct where flow properties can be assumed to be uniform. This data would be interesting to compare against the last column of transducers in the mixing interface to see how flow properties change as they propagate downstream. It would also be good for capturing supersonic data if any oblique shock structures develop aft of the last row of pressure transducers.

Another problem that needed to be addressed is the transducer drift due to temperature effects. This issue will only get worse as the presence of an actual detonating PDR will expose some transducers to hot flow while others in the flow path of the wind tunnel will continue to cool. PCB®, aware of this problem, makes temperature regulated jackets for transducers. The jackets allow water to flow around the transducers making them insensitive to temperature changes in the flow. Integrating water lines may prove to be difficult with the limited space in the wind tunnel, but some mechanism will need to be implemented to take this effect out of the system.

The high frequency runs also indicated that the rotary valve is not sufficient for regulating the fuel/oxidizer supply to the PDR. At higher frequencies, the slug of gases injected into the system is reduced, since in-phase exposure time of the valve is inversely proportional to the frequency of the motor. Because of this, a rotary valve can only be optimized for a single condition. Work at the ARC at UTA is progressing toward digital solenoid valve injection into PDR systems. It would be beneficial to
eventually integrate a similar system controlled by computer in this experiment to get a true “apples to apples” comparison of data at different rates.

If additional cold flows are to be done, the system needs to be further modified to ensure that the model is ejecting a supersonic jet into the secondary flow. The expansion ratio on the current experiment is much too large given the available pressure and mass flow to experience a total supersonic solution.

![Figure 4.1 Potential modifications to CD nozzle insert](image)

Figure 4.1 Potential modifications to CD nozzle insert

One possible solution is to modify the CD nozzle insert. If the lower surface was parallel to the axial direction, the expansion would be limited to the taper in the splitter plate. While this would blank out the entire upper row of transducers, it would also return the model to a constant-area duct, and reduce the complexity of the problem that the continual expansion imposes.
APPENDIX A

ERROR ANALYSIS
This is the uncertainty analysis done for the calculations made in this set of experiments. It follows the methodology laid out in Holman\textsuperscript{[10]}.

**In determining pressure ratios:**

\[
\frac{P_{\text{static}}}{P_{\text{amb}}} = \frac{P_{\text{trans}} + P_{\text{amb}}}{P_{\text{amb}}}
\]

Eq. A.1

The uncertainty in the ambient pressure reading is \(\pm 0.01\) psi (\(\pm 68.9\) Pa). The PCB\textsuperscript{®} transducers have an uncertainty of \(\pm 0.05\) mV/psi (\(\pm 0.73\) mV/kPa). With the scaling factor and sensitivity setting applied to the data acquisition system for these experiments, this translates into a \(\pm 0.1\) psi (\(\pm 689\) Pa) uncertainty. The uncertainty calculation for the equation above is as follows.

\[
W_{PR} = \left[ \left( \frac{\partial PR}{\partial P_{\text{amb}}} w_{\text{amb}} \right)^2 + \left( \frac{\partial PR}{\partial P_{\text{trans}}} w_{\text{trans}} \right)^2 \right]^{\frac{1}{2}}
\]

Eq. A.2

\[
\frac{\partial PR}{\partial P_{\text{amb}}} = \frac{1}{P_{\text{amb}}} - \frac{P_{\text{trans}} + P_{\text{amb}}}{P_{\text{amb}}^2}
\]

Eq. A.3

\[
\frac{\partial PR}{\partial P_{\text{trans}}} = \frac{1}{P_{\text{amb}}}
\]

Eq. A.4
With this known the fully expanded uncertainty analysis still depends on the actual values of ambient pressure and transducer pressure as seen below.

$$W_{PR} = \left[ \left( \left( \frac{1}{P_{amb}} - \frac{P_{trans} + P_{amb}}{2} \right) \pm 0.01 \right)^2 + \left( \frac{1}{P_{amb}} \right)^2 \right]^{\frac{1}{2}}$$

Eq. A.5

In the model, for pressure ratios very close to 1, indicating ambient conditions as experienced in the inlet of the model for Mach 0 testing, the error is ±0.007. The maximum pressure ratios seen in the PDR reached values of 2.8. At this value the error still is very close to ±0.007 indicating that the error in pressure ratio is relatively insensitive to the actual pressure ratios. This value will therefore be carried through the rest of the error analysis as a fixed value.

In determining Mach number:

$$\frac{P_{static}}{P_{total}} = \left[ 1 + \frac{\gamma - 1}{2} \frac{M^2}{\gamma - 1} \right]^{-\frac{\gamma}{\gamma - 1}}$$

Eq. A.6

This equation can be inverted to give Mach as a function of pressure ratio instead of vice versa. After some rearranging of terms, it takes the following form.
\[
M = \sqrt{\frac{2}{\gamma - 1} \left[ \left( \frac{P_{\text{static}}}{P_{\text{total}}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]}
\]

Eq. A.7

The error analysis on this term goes as follows. The pressure ratio from this point on will be referred to as PR for simplicity.

\[
W_M = \frac{\partial M}{\partial PR} W_{PR}
\]

Eq. A.8

\[
\frac{\partial M}{\partial PR} = \frac{-1}{\gamma} PR^{-2\gamma + 1} \gamma
\]

\[
\frac{\partial M}{\partial PR} = \frac{-1}{\gamma - 1} \sqrt{\frac{2}{\gamma - 1} \left[ \left( PR \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]}
\]\n
Eq. A.9

Again, a fully expanded form of the error still requires knowledge of the pressure ratio in question.

\[
W_M = \frac{-1}{\gamma} PR^{-2\gamma + 1} \gamma
\]

\[
W_M = \frac{-1}{\gamma - 1} \sqrt{\frac{2}{\gamma - 1} \left[ \left( PR \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]} W_{PR}
\]

Eq. A.10

Because of the dependence on the pressure ratio value, the error in Mach number can not be set for all possible values.

Looking at the wind tunnel, the pressure ratio between the test section and the plenum chamber was 0.090 with an error of ±0.01. With these values, it is expected to see an error in Mach number from the wind tunnel of ±0.071.
On readings from the model in the inlet, pressure ratios are very close to 1. A pressure ratio of exactly 1 allows the denominator of Eq. A.10 to go to a value of 0, indicating that the error becomes infinite. If using a value of 0.995 for pressure ratio as was seen in the steady-state and high frequency static tests and a value of ±0.007 for the pressure ratio error as was discussed earlier, the error in Mach number is ±0.059. This may not appear to be significant upon first inspection, especially considering the Mach number error for the wind tunnel is larger, but that has to be balanced with the actual Mach numbers associated with each. The wind tunnel data indicated that the Mach number for the supersonic tests were 2.23 which indicates that the error is only 3.2% of the total Mach. On the other hand, the static measurements indicated that the Mach number in the inlet was 0.085 which indicates that the error is 69.4% of the total Mach. This was the case for the steady-state and high frequency test.

For the low frequency static test in which the pressure ratio was 0.988 in the inlet, an error of ±0.039 is predicted in Mach number. This is only 29.7% of the total Mach (0.13) at this condition.

In determining mass flow:

Mass flow is fairly complex given the number of variables it is dependent on as well as the complexity of the equation. Recall the mass flow parameter definition in Eq. 3.4.

\[
MFP(M) \equiv \frac{m}{P_t A} \sqrt{\frac{T_t}{\gamma}} = \frac{M \sqrt{\gamma R}}{P_t A \left[ 1 + \frac{(\gamma - 1)}{2} M^2 \right]^{(\gamma + 1)/(\gamma - 1)}} \quad \text{Eq. A.11}
\]
This equation needs to be rearranged to have the mass flow as the only dependent variable.

\[ \dot{m} = \frac{P_t A}{\sqrt{T_t}} \frac{M \sqrt{\gamma R}}{\left[ 1 + \left( \frac{(\gamma-1)}{2} M^2 \right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \right]} \]  

Eq. A.12

For the error analysis here, there are three variables that the mass flow is dependent upon: Mach number, total pressure, and total temperature.

\[ w_m^* = \left[ \left( \frac{\partial m}{\partial M} w_M \right)^2 + \left( \frac{\partial m}{\partial P_t} w_{P_t} \right)^2 + \left( \frac{\partial m}{\partial T_t} w_{T_t} \right)^2 \right]^{\frac{1}{2}} \]  

Eq. A.13

Because of the complexity of this equation, a fully expanded form will not be shown.

Here are the individual derivatives seen in the equation.

\[ \frac{\partial m}{\partial M} = \frac{P_t A}{\sqrt{T_t}} \frac{M \sqrt{\gamma R}}{\left[ 1 + \left( \frac{(\gamma-1)}{2} M^2 \right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \right]} \frac{1}{2} \left( \frac{\gamma + 1}{\gamma - 1} \right) M^2 \]  

Eq. A.14

\[ \frac{\partial m}{\partial P_t} = -\frac{P_t A}{\sqrt{T_t}} \frac{M \sqrt{\gamma R}}{\left[ 1 + \left( \frac{(\gamma-1)}{2} M^2 \right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \right]} \]  

Eq. A.15
\[
\frac{\partial m}{\partial T_i} = \frac{-AP_i}{2\sqrt{T_i^3}} \frac{M\sqrt{\gamma} R}{\left[1 + (\gamma - 1) / 2\right]M^2} \left[\gamma^2 + 1 + 2(\gamma - 1)ight]^{-1/2} 
\]

Eq. A.16

The mass flow for the PDR ejector was calculated at the throat assuming that this point would be experiencing a Mach number of exactly 1. Total temperature was also assumed to be at room temperature for the PDR itself. That leaves total pressure as the only mass flow dependence. Given these assumptions, the uncertainty in mass flow for the PDR is ±0.000105 kg/sec. This value remains fixed for all cases.

For the inlet mass flow on the static runs, the dependence on temperature and Mach number come back. Total pressure and total temperature conditions were assumed to be ambient air and the tolerances on the instruments measuring them were ±0.01 psia (±68.95 Pa) and ±1° F (±0.56 K) respectively. For Mach number, the error is specific to the run itself, and can be taken from the Mach error analysis above.

For the steady-state and high frequency runs, the uncertainty in mass flow is ±0.107 kg/sec. For the low frequency runs, the uncertainty is ±0.071 kg/sec. Again, the main reason the low frequency run has less error has to do with the better prediction of Mach number, as the total pressure ratio for this case was further away from 1.
APPENDIX B

HIGH FREQUENCY SUPersonic RUN DATA
Due to the disparity in the mass flow between the secondary flow and the primary flow, there was no net effect from frequency. All the discussion on the test results are explained in the low frequency data. These graphs are here only for reference and to verify that the two conditions at supersonic speeds showed little to no difference as previously stated.

Figure B.1 Supersonic wind tunnel pressure readings for high frequency runs
Figure B.2 Supersonic high frequency PDR pressure readings

Figure B.3 Supersonic high frequency inlet pressure readings
Figure B.4 Supersonic high frequency mixing interface pressure readings (bottom)
Figure B.5 Supersonic high frequency mixing interface pressure readings (top)
REFERENCES


BIOGRAPHICAL INFORMATION

Justin "Tyler" Nichols was born in Carbondale, IL on February 29, 1980. He moved to Mansfield, TX in April of 1982 with his family, where he attended Erma Nash Elementary School, Mary Orr Intermediate School, Worley Middle School, and Mansfield High School for his primary education. Upon graduation, in June of 1998, he started at the University of Texas at Arlington studying Aerospace Engineering in the MAE department. He acquired his Bachelors of Science degree in May of 2002 and immediately began work on a Masters of Science in that same field, still at UTA. This paper documents the independent research that he has done in attaining that degree.