THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF AEROSPACE ENGINEERING

PULSEJET FLOW DYNAMICS UTILIZING A 1-D NUMERICAL MODEL

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of the requirements
for a baccalaureate degree
in Aerospace Engineering
with honors in Aerospace Engineering

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ABSTRACT

The pulsejet is one of the earliest ways to show the fundamental interactions between fluid flow and pressure waves. Though they are simple to make, their gas dynamics provide an excellent starting point to investigate fluid flow phenomena. This study of a pulse jet is an initial attempt to discover and understand how the flow through a simple pulse jet engine determines performance. The flow was modeled using Computational Fluid Dynamics based on MacCormick's quasi one-dimensional numerical model. This method uses Euler equations to determine the pressure, density, and velocity at each time step and position along the tube. This analysis will use experimental results as a comparison of the performance against the calculated performance. It is expected the pressure and velocity will fluctuate in an oscillatory manner due to the reflected pressure waves at the end of the tube. Extracting the frequency, it can be shown that the inlet and exit frequencies match up for maximum thrust. Evaluating these results show why pulsejets are again becoming a popular study in the aerospace industry.

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Chapter 1

Introduction

The pulse jet is to be considered the simplest propulsion devices. The only moving part found in a pulsejet is the reed valves that prevent flow reversal in the combustion chamber. The pulsejet is operated by using acoustic waves that provide oscillatory changes in pressure.

In the early 1900s pulsejets were seen as a simple, low cost, and high thrust to weight ratio propulsion devices for next generation aircraft [1 2]. Credit can be given to the early engineer Paul Schmidt who designed the first operational pulsejet known as the Schmidt tube. During World War II, the V-1 ("flying buzz bomb") was the first unmanned aircraft to utilize the Schmidt tube. One of the main advantages engineers saw was the self-compressing ability of the pulsejet. Without having a turbine to power a compressor, all of the energy from the combustion process can be used to provide thrust [3]. During this time of war and unrest, many variations of the Schmidt tube have been proposed, but the focus slowly died off as the turbojet showed more promise in performance and scalability. The turbojet was already being used for fighter jets and commercial aircraft and it was clear the turbojet was the future.

The pulsejet is considered an unsteady propulsion device that generates intermittent thrust [4]. When the pressure in the combustion chamber is below atmospheric pressure, the reactants flow into the chamber. The residual heat and the heat transferred from the walls increase the reactants temperature until ignition and combustion of the reactants. The combustion process causes an increase in the chamber pressure and the hot gases get pushed down the exhaust. The hot gases leave the exhaust at high velocities that generate the pulsejet's thrust. At the end of the exhaust, the hot gases are nearly expanded to atmospheric pressure. Due to the constant exit exhaust pressure, an expansion wave is reflected back done the exhaust tube towards the combustion chamber. When the pressure wave reaches the combustion chamber the pressure is sub-atmospheric and causes the reed valves to open, letting in fresh reactants. As the reactants are pulled in the pressure increases above atmospheric, closing the reed valves and the cycle repeats. Though many variations were created during World War II, the basic design and function of the pulsejet remains the same. A schematic of a hobby-scale pulsejet can be found in Figure 1.

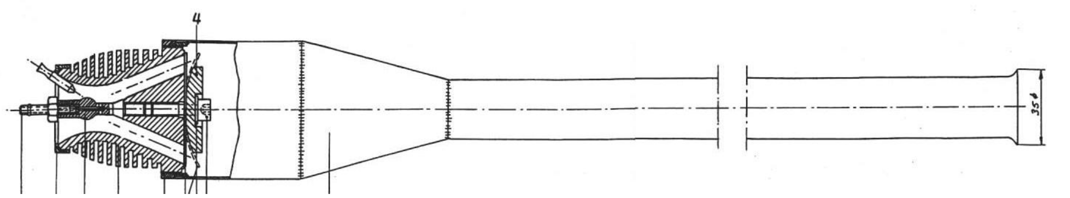


Figure 1. Schematic of a Valved Hobby-Scale Pulse Jet

Early research has shown that pulse jets decrease in efficiency as they are scaled up. Again, another reason why they were put aside for the turbojet. Now that UAVs and other small unmanned aircraft are continuously being developed, the search for simple, low cost, and high thrust propulsion devices could bring the pulsejet back to life.

Chapter 2

Numerical Method

The numerical method used to model the flow through the pulsejet was based on the MacCormick method for an unsteady shock tube [5]. This method is referred to as a shock-capturing method. Compared to the shock-tracking method, this method is much simpler to implement in a programming sense because keeping track of the flow discontinuities is not needed. However, the boundary conditions require a special approximation that can easily be integrated to determine the inlet and exit conditions. This method is assuming no heat transfer during the process.

2.2 Governing Equations

The model uses the Euler equations for one-dimensional flow by Eq. 1,

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} = 0 \qquad (1)$$

where Q and E are given by Eq. 2 and 3.

$$Q = \begin{vmatrix} \rho \\ \rho u \\ E_t \end{vmatrix}, \; E = \begin{vmatrix} \rho u \\ \rho u^2 + p \\ (E_t + p)u \end{vmatrix} \qquad (2)$$

$$E_t = \rho \left[\frac{p}{\rho(\gamma - 1)} + \frac{u^2}{2} \right] \qquad (3)$$

The MacCormack method applies a two-step predictor-corrector scheme given by Eqs. 4, 5 and 6; similar to the two-step Lax-Wendroff scheme. More detail on the two-step Lax-

Wendroff can be found elsewhere [6]. The predictor values are defined by $\left(t^{n+1/2}, x_i\right) \equiv \bar{Q}_i$ with the convective flux term E representated by forward differences. The corrector step values are defined the same way as the predictor step, but the convective flux is now represented by backward differences. The predictor step is given by:

$$\bar{Q}_i = Q_i^n - \frac{\Delta t}{\Delta x}(E_{i+1}^n - E_i^n) \tag{4}$$

The corrector step is given by:

$$\bar{\bar{Q}}_i = Q_i^n - \frac{\Delta t}{\Delta x}(\bar{E}_i - \bar{E}_{i-1})$$

$$E_i^{n+1/2} \equiv \bar{E}_i \tag{5}$$

The updating step is given by:

$$Q_i^{n+1} = \frac{1}{2}\left(\bar{Q}_i + \bar{\bar{Q}}_i\right) \tag{6}$$

2.3 Boundary Condition Approximation

The predictor and correction steps mentioned previously cannot be used to determine the boundary conditions at the inlet and exit. Because the flow is traveling subsonic; the upwind boundary approximation the boundary conditions is given by, where J is the last node:

$$p_J^{n+1} = P_e \tag{7}$$

where p_e is the exit pressure at the exhaust. From here, ρ_J^{n+1}, e_J^{n+1}, and u_J^{n+1} can be determined by the following equations:

$$\rho_J^{n+1} = \rho_J^n - \left(\frac{dt}{dx}\right)\left(\rho_J^n u_J^n - \rho_{J-1}^n u_{J-1}^n\right) \tag{8}$$

$$e_J^{n+1} = e_J^n - \left(\frac{dt}{dx}\right)\left(\left(\frac{(e+p)u\rho}{\rho}\right)_J^n - \left(\frac{(e+p)u\rho}{\rho}\right)_{J-1}^n\right) \tag{9}$$

$$u_J^{n+1} = \sqrt{\frac{2\left(e_J^{n+1} - \frac{p_J^{n+1}}{gamma-1}\right)}{\rho_J^{n+1}}} \tag{10}$$

The inlet boundary approximation is determined using Eqs. 7-10. However, J = 0 and the right hand side components are now J = J+1 and J-1 = J

Chapter 3

Initial Problem

A one meter long pulsejet has been selected for this analysis. This value is about double the size of a normal hobby scale pulsejet. It was chosen to provide a better visual on how the compression wave and reflected expansion wave travel along the exhaust tube. Initially no flow is moving inside the pulse jet, so the flow velocity was set to zero along the length of the tube. In order to start the pulse jet a pressure gradient must be implemented to pull and exhaust the inlet and combusted gas. Using atmospheric conditions of temperature at 273 Kelvin and pressure at 101.325 kPA, and the perfect gas law, the pressure gradient at the midpoint of the exhaust tube has a value of two. The hyperbolic tangent was used to smooth the steep pressure gradient to generate a smoother progression of the compression wave and reflected expansion wave inside the tube. Using the perfect gas law the density of the gas along the exhaust tube was determined. The setup can be seen in Figure 2, on the following page.

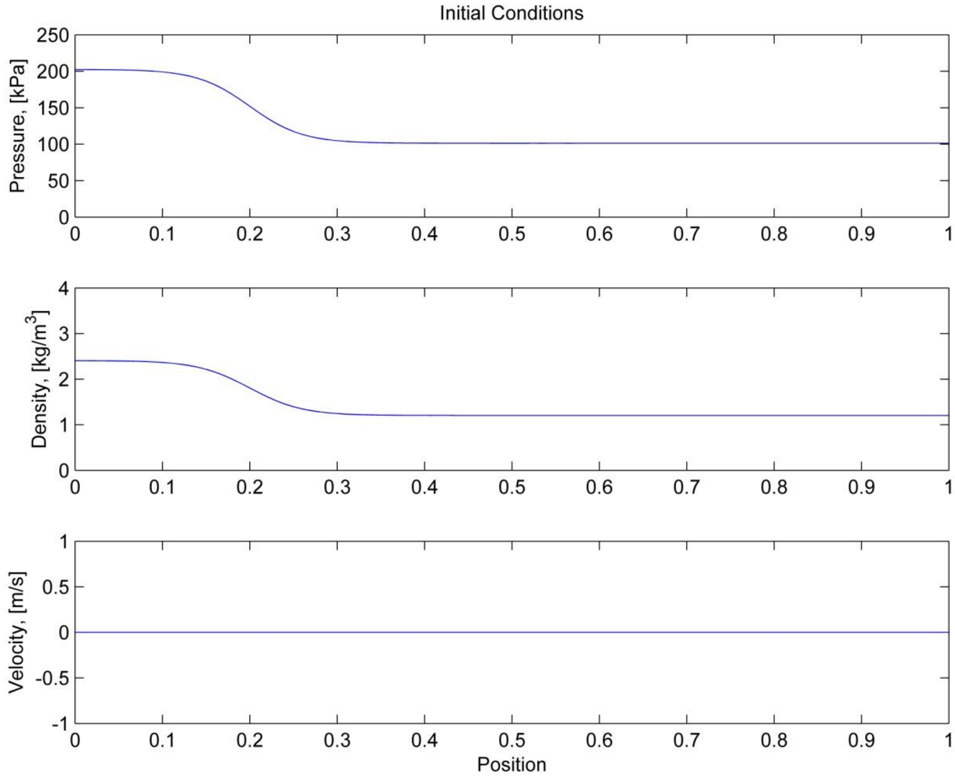


Figure 2: Initial Conditions

Chapter 4

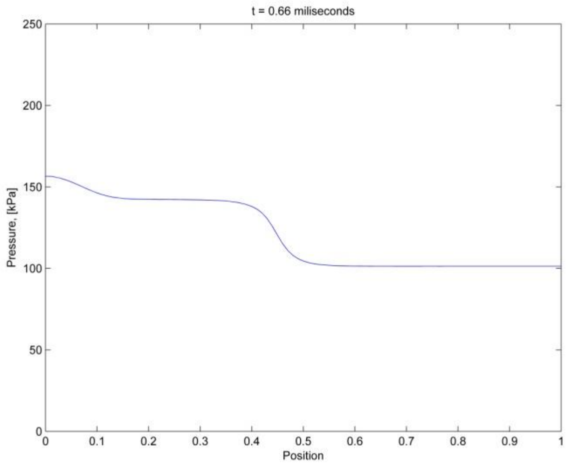
Results

The purpose of this paper was to analyze the gas flow through a pulsejet, as stated in the introduction. The pulsejet is operating in sub-sonic flow conditions with zero friction and heat loss.

Based on the ideal pulsejet it is expected to see a compression wave travel to the exhaust exit and reflect back as a rarefaction wave with an initial pressure equal to the atmospheric pressure. At the open end the reflected rarefaction wave will travel back through the exhaust tube into the combustion chamber. The velocity of the gas should increase and be a maximum at the exit of the exhaust. As the rarefaction wave travels back into the combustion chamber the velocity of each wave, the inlet expansion wave and rarefaction wave, should be equal during the combustion process. This is an indication of combustion chamber ignition [7].

As the compression wave travels towards the exhaust exit, the pressure in the combustion chamber should drop and cause an expansion wave to travel towards the inlet of the pulsejet. This expansion wave will then reflect in like sense as another expansion wave.

From the results it can be shown that the numerical method chosen follows the assumptions and expectations of the ideal pulsejet initially.



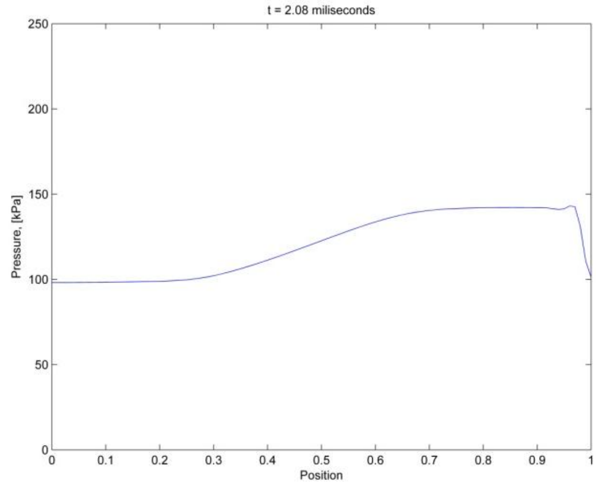


Figure 3: (Left) Pressure Distribution after Ignition

Figure 4: (Right) Compression Wave Propagating Towards Exhaust Exit

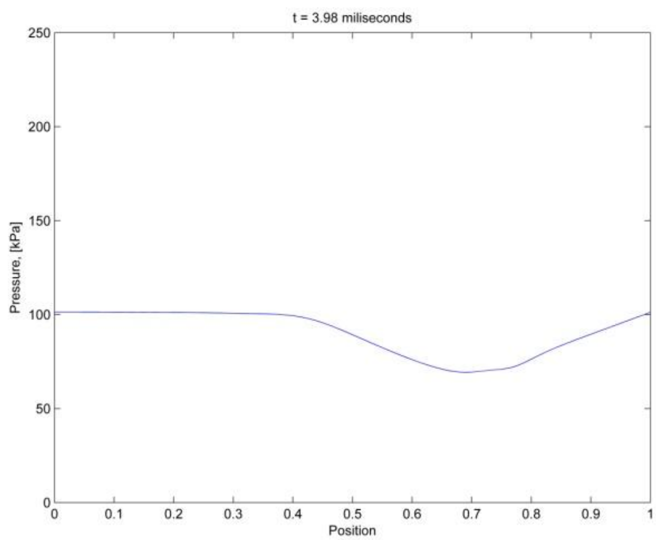


Figure 5: Reflected Rarefaction Wave

Figures 3-5, show the wave propagation throughout the pulsejet. The initial wave of hot gases begins by propagating down the exhaust tube as a compression wave. This was expected because the compression wave provides the thrust by increasing the exit velocity and pressure gradient out the exhaust. As the compression wave strikes the open boundary at the exit, it is expected to reflect as a rarefaction wave. The pressure will drop due to flow expansion, as seen in Figure 5. It appears that the pressure in the combustion chamber at the time of ignition after the first cycle is highly dependent on the exit boundary conditions. This small pressure gradient has the ability to degrade the pulsejet’s performance as the specific fuel consumption would decrease [7].

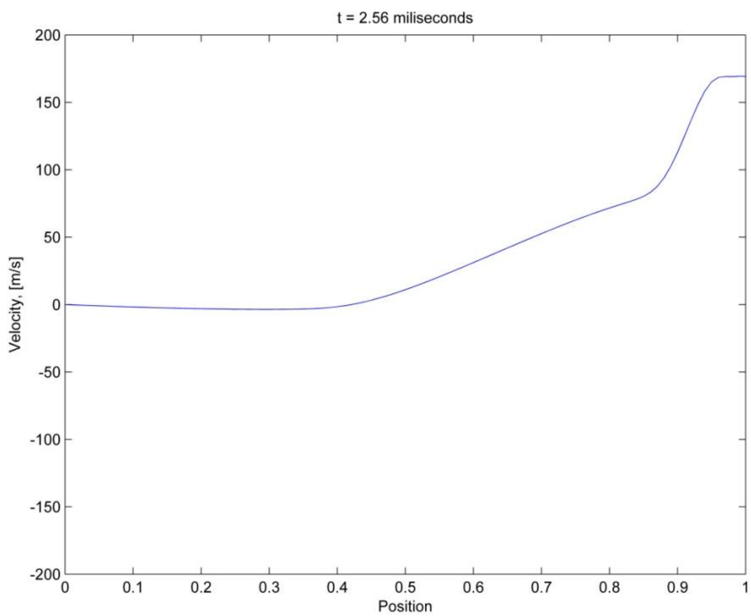


Figure 6: Velocity Profile when Compression Wave Strikes the Open Boundary

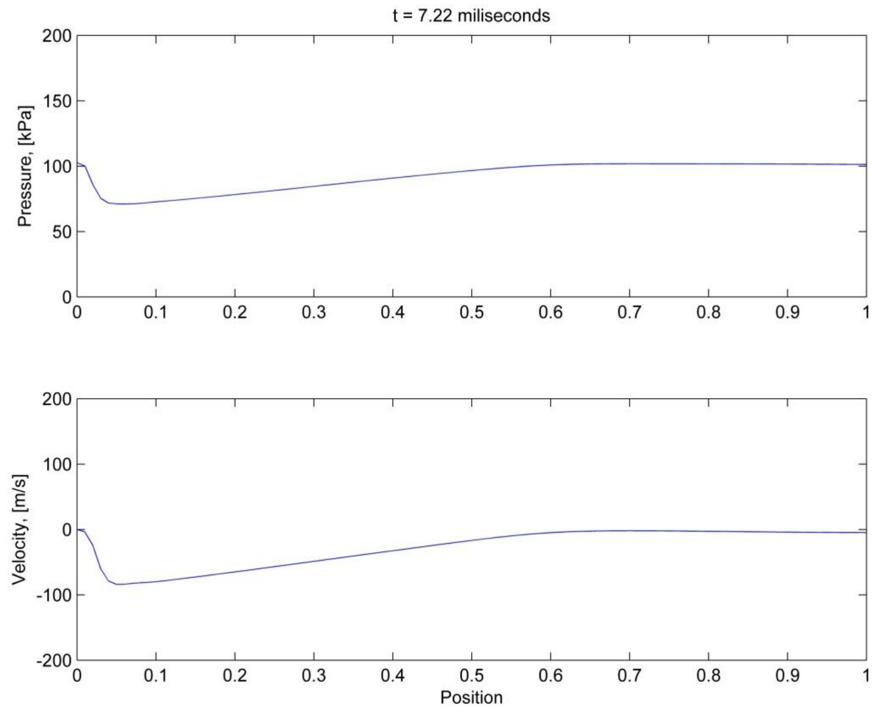


Figure 7: Flow Velocity Decrease and Backflow in the Combustion Chamber

There appears to be a correlation between the velocity magnitude and operation phase of the pulsejet. It is shown in Figure 6, on the previous page, the maximum flow velocity occurs at the exhaust exit where the thrust is being produced. When the reactants are mixed in the combustion chamber the flow velocity decreases as the kinetic energy of the flow is reduced in the chamber for ignition. It is determined that the backflow of hot gases from the reflected rarefaction wave causes the flow velocity to become negative, indicating that not all of the exhaust gases were ejected from the exhaust tube. Figure 7 shows a great representation how the flow velocity decreases right before combustion and how previously combustion hot gases reenter the combustion chamber due to backflow. All of these flow behaviors can be altered by changing the length and adding an exhaust tip flare to produce the performance required.

This specific pulsejet used in the analysis has the performance behavior that was expected, but over time the performance began to decrease. In Figure 8, there is a clear distinction the pulsejet does indeed produce intermittent thrust. These results were founding by applying the general thrust equation to the exhaust boundary. One thing to notice is how the thrust is decreasing over time. It is suspected with this behavior that the pulsejet will extinguish after a certain amount of time, allowing no more thrust to be generated. This can be a factor as the density is not kept constant inside the pulsejet; allowing a decrease in reactants to enter the combustion chamber each cycle therefore reducing the mass flow on each cycle.

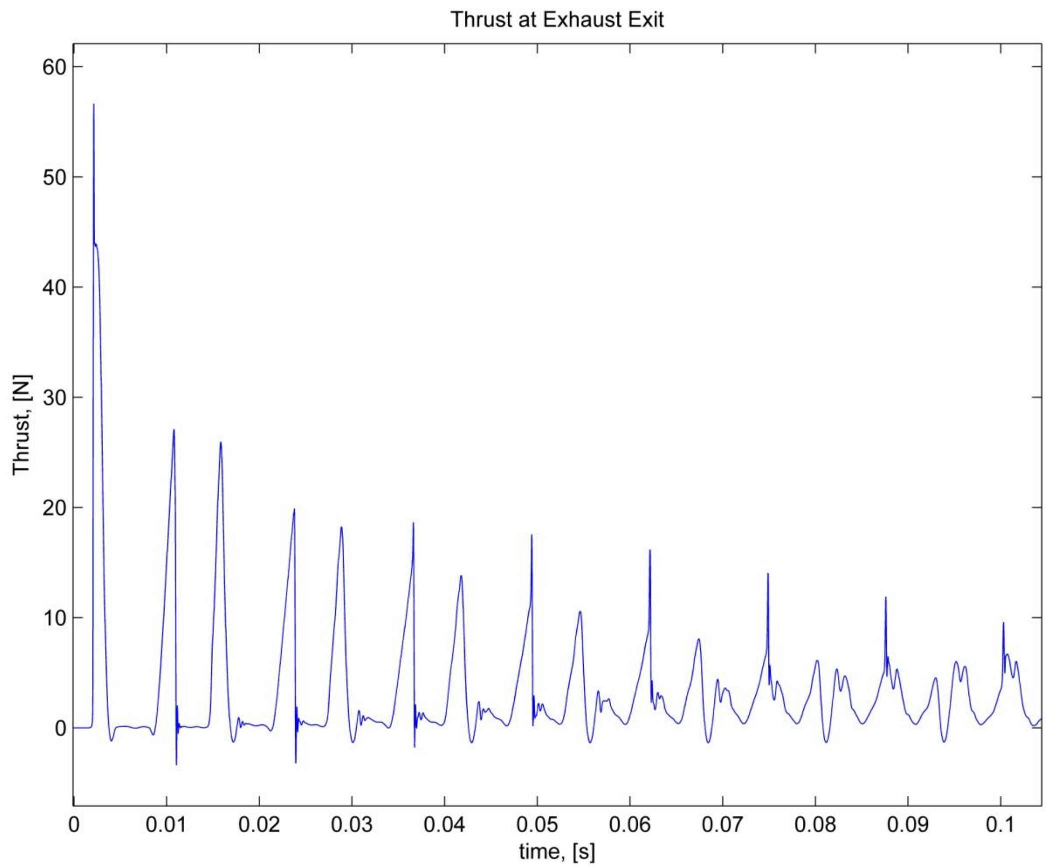


Figure 8: Thrust Produced by the Pulsejet

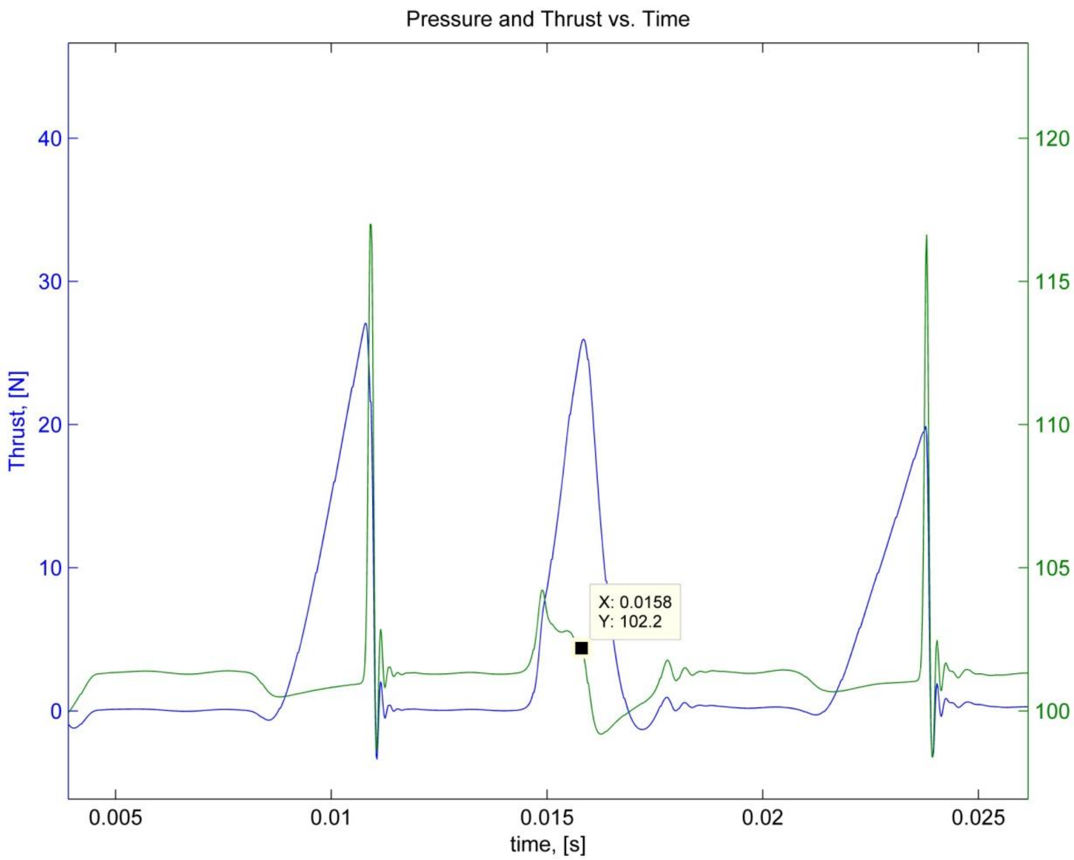


Figure 9: Pressure Overlay on Thrust

From the general thrust equation, the results show the pulsejet obtains maximum thrust when the exit pressure is equal to the ambient pressure just outside the exhaust boundary. When the pressure is larger than atmospheric pressure not all of the momentum is being transfer to axial thrust; instead some of the momentum is being dispersed radially. When the pressure is below atmospheric pressure an adverse pressure is created and the pulsejet experiences backflow into the exhaust, reducing the overall thrust.

Chapter 5

Conclusion

This paper studied the effects of unsteady flow through a pulsejet. It is considered the simplest air-breathing jet due to its very few moving parts, but it is one of the most complex jets to analysis due to its unique dynamic flow. This model uses the one-dimensional MacCormick method for subsonic flow as a great numerical approximation. From the analysis, it was shown that:

1) The pressure wave is the main driver behind the pulsejet performance. It guides how quickly the flow velocity rises and determines the frequency of the pulsejet.
2) The reflected rarefaction wave at the open end of the exhaust causes hot gas backflow as the gas expands and returns into the combustion chamber. The backflow can hurt performance but one benefit is it raises the temperature of the fuel and air mixture to reduce the energy loss during combustion.
3) The combustion chamber pressure appears to be highly dependent on the exit boundary conditions. The chamber pressure is slightly higher than the ambient pressure during the mixture process.
4) The velocity profile can be directly related to the phase of the pulsejet cycle, by the magnitude and sign. As expected, the flow velocity is a maximum as the compression wave strikes the open end of the exhaust to provide the pulsejet's thrust. The backflow and reflected rarefaction wave are represented by a negative flow velocity, and the

combustion process requires the flow velocity to decrease to its minimum velocity in magnitude.

5) The thrust produced has a tendency to decrease over time until no thrust is being produced. This is likely an occurring from the fluctuating density inside the pulsejet. A more true representation would be to hold the density constant as the temperature changed with time. This should keep the mass flow constant and equal intermittent thrust.
6) Maximum thrust is obtained when the exit pressure at the exhaust is equal to the ambient pressure outside.

Current work is being done to determine the thrust when density is kept constant with changing temperature. Using the same initial conditions, the length of the pulsejet can be altered to optimize its performance by controlling the pulsejet frequency.

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Appendix A

Nomenclature

Q	=	momentum flux
E	=	convective flux
E_t	=	total energy per unit volume
ρ	=	density
p	=	pressure
u	=	velocity
γ	=	heat capacity ratio
u_j^n	=	u(x,t)
P_e	=	exit/ambient pressure
e	=	total energy per unit volume

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