GENG, TAO. Numerical Simulations of Pulsejet Engines. (Under the direction of Dr. William L. Roberts.)

The pulsejet has recently received more research interests due to its simple design, which can be developed into low-cost micro-scale propulsion devices for use in many of today’s new applications such as UAVs. However, the relatively low thermal efficiency of pulsejets has always been the major obstacle in their development. The goal of this research is to investigate the possibility of using pulsejets in certain applications where the pulsejet can trade its low efficiency with low cost, simple design, and light weight.

This work investigates pulsejet operation in a combined experimental and numerical approach, although the focus here is on the computational research. The fluid mechanics, acoustics, and chemical kinetics are studied numerically to understand the physics behind pulsejets and their operations. The research objectives include miniaturization of valveless pulsejets, acoustics model developments for both valved and valveless pulsejets, obtaining preliminary thrust performance data on micro-scale pulsejets, and finally, the formation of the starting vortex ring and its effect on pulsejet thrust.
Numerical Simulations of Pulsejet Engines

by
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1 Introduction

1.1 Pulsejet Background

During WW-II Germany used pulsejets to power the V-1 “buzz bomb”, shown in Figure 1-1. The huge noise and low cost of these engines make them suitable for the short-distance bombing mission. The pulsejet received considerable research interest after WW-II. However, soon people found that the overall low thermodynamic efficiency, noise, and short-lived valves associated with the pulsejet make it much less competitive than gas turbine engines. Without continuous investments in research, the pulsejets soon gave way to gas turbine engines as the propulsion option of choice after the middle of 20\textsuperscript{th} century. However, during the past few years, pulsejets have gained research attention because of their low cost and light weight which maybe utilized in many new propulsion concepts. One of the applications is to power radio-controlled vehicles or UAVs using small scale or micro scale pulsejets.

The most significant and technically challenging aspect of the micro-propulsion device is its limited residence time (Waitz et al., 1998). Once the combustion chamber size becomes 2 to 3 orders of magnitude smaller than that of a large scale jet engine, the residence time within the combustion chamber approaches the characteristic chemical kinetic time scale for hydrocarbon-air reactions. This is the biggest reason for moving away from traditional jet fuels and using hydrogen (Majumdar & Tien 1998). In some cases, it may even be necessary to premix and preheat the fuel and air upstream of the combustion chamber in order to speed up the chemical kinetic time scale. It also has
been suggested by Waitz et al. (1998) that increasing the combustion chamber size relative to the engine size will help with the very small residence times. To solve these problems, a better understanding of the theories and physics behind the pulsejets is needed.

Generally the operating frequency of a pulsejet, \( f \), is considered to be a function of pipe length, \( L \).

\[
\frac{f}{a} = \frac{1}{4L}
\]  

(1-1)

where ‘a’ is the speed of sound. This is the so-called quarter-wave model of the pulsejet frequency. This means that the acoustics waves must travel through pipe 4 times in each cycle. However, it is not clear whether this acoustic model is valid for all kinds of pulsejets designs. For example, the acoustic model for a valveless pulsejet with a forward-facing-inlet configuration like the U-shaped Lockwood-Hiller pulsejet shown in Figure 1-2 will most likely be fundamentally different. Also of interest is how the operating frequency changes with the combustion chamber volume. These questions need to be answered before the design and optimization of a pulsejet for a certain application can begin. More importantly, how to make a small scale pulsejet generate reasonable thrust is more challenging.

The only way to generate thrust is to convert heat energy into kinetic energy by expanding the combustion products from a pressure higher than atmospheric pressure to atmospheric pressure (Tsien, 1946). This high pressure can be generated by two simple methods: ram compression or constant-volume combustion. A common device utilizing
the first method is called a ramjet and a device utilizing the second method is called a pulse detonation engine. Both the pulse detonation engine and pulsejet are unsteady propulsion devices that generate intermittent thrust. Considerable experimental research efforts have been focused on maximizing the thrust from these devices. It is believed that by adding an unsteady ejector, or thrust augmenter, at the end of the exhaust pipe, thrust from a pulse detonation engine or pulsejet can be improved. Many pulsejets have been built with a flare at the end of the exhaust pipe to increase thrust. Since this expansion process occurs at the exit of the pulsejets, it is important to understand the pulsejet exhaust flow, which is dominated by starting vortex rings.

An early study of vortex rings generated by an unsteady jet was performed by Gawthrop et al. (1931) who established the existence of the vortex ring at the orifice of a shock tube. Elder and Haas (1952) conducted an experimental study of the formation and acceleration of the vortex ring at the open end of a cylinder shock tube. Siekmann (1963) presented a theoretical analysis of the unsteady periodically working jet propeller, whose design was based on the propelling mechanism of certain aquatic animals such as squid. However, none of these vortex investigations were directly applicable to a pulsejet. Gharib et al. (1998)) were the first to relate starting vortex rings to a propulsion device. Their results show that the Formation number, defined as the limiting value of \( \frac{L}{D} \) (vortex rings generated above this limiting value of \( L/D \) do not absorb all of the discharged fluid’s mass or vorticity), is between 3.6 and 4.5, suggesting that a universal value for the Formation number may exist. Paxson and Wernet (2004) investigated the unsteady thrust augmentation using a speaker-driven jet. Their results show that the
Formation number is a relevant, although not sufficient, parameter for evaluating the performance of an unsteady ejector. More recently, Krueger and Gharib (2003) studied the significance of vortex ring formation to the impulse and thrust of a starting jet. Using two different piston velocity profiles they showed that the starting vortex ring formation and pinch off (defined as the state at which vortex ceases to accept additional vorticity from the shear layer) is critical to the thrust and impulse produced by starting jets. It was also found that the nozzle exit over-pressure contributed as much as 42% of the total impulse for cases involving isolated vortex rings. However, as they stated, the hypothesis that the vortex ring pinch off is significant for propulsion relies on the relative significance of the leading vortex ring to the trailing jet for generating thrust. Although no attempt was made to design a real pulsed-jet device to examine their conclusions, Krueger and Gharib (2003) made some suggestions for such unsteady propulsion devices such as synthetic jets.

1.2 Research Objectives

The research objective of this work was to investigate the fluid mechanic, acoustic, and thermodynamic processes of pulsejets with various designs and configurations. Numerical simulations are used to provide physical insights into the pulsejet’s operation and help experimental personnel to build a micro scale pulsejet. The operating cycle for various pulsejet designs are studied and a more complex acoustic model that accounts for the combustion chamber volume, inlet and exhaust pipe geometry is proposed. The exhaust flow of a 50 cm valved pulsejet is studied to
investigate the effect of the starting vortex ring on pulsejet thrust. Based on the simulation results, an optimal flare is designed to improve thrust performance. A characteristic parameter in the field of vortex ring study, formation number, will be defined for pulsejet-generated vortex rings and compared with those generated by piston-cylinder devices.

This research uses a combined experimental and numerical approach to investigate the characteristics of pulsejets. Three different pulsejets are studied numerically in this thesis. Chapter 2 provides an introduction to valveless pulsejets and the corresponding simulation model. Scalability, inlet orientation, and fuel flow rate are discussed. The simulation results are validated by experimental data. Chapter 3 will discuss the simulation of an 8 cm valveless pulsejet with the inlets facing rearwards. The operation frequency, cycle, and thrust of this pulsejet are presented. In chapter 4, a 50 cm valved pulsejet is simulated. Based on experimental data, a detailed valve model and combustion model are used in the simulation. Simulation results are compared with experimental data and the valved pulsejet operation cycle is illustrated. Chapter 5 focuses on the starting vortex rings generated by the 50 cm valved pulsejet exhaust flow. The starting vortex ring properties, such as circulation, pinch off time, and formation number are calculated. Different flare designs are simulated to learn their effects on vortex rings and pulsejet thrust and compared with experimental measurements. Finally, chapter 6 provides a summary and recommendation for future work.
Figure 1-1 V-1 buzz bomb

Figure 1-2 The U-shaped Lockwood-Hiller valveless pulsejet engine
2 Combined Numerical and Experimental Investigation of a 15-centimeter Valveless Pulsejet

2.1 Introduction

The pulsejet is an unsteady propulsion device that generates intermittent thrust. Due to its simple design and near constant-volume combustion, the pulsejet has received considerable research attention since the beginning of the 20\textsuperscript{th} century. The first practical application of the pulsejet was the German V-1 ‘buzz bomb’ in World War II. Based on the inlet design, pulsejets can be classified as either valved or valveless. An early study (Tsien, 1946) on pulsejets found that the reed valves flapping at high frequencies in the valved pulsejets could be easily damaged at high temperature. This generated interest in finding more reliable designs such as valveless pulsejets to improve the performance and reliability.

In 1909, a patent was issued for a valveless pulsejet, where the reed valve was replaced with an “aerodynamic valve” (Ogorelec, 2002). As shown in Figure 2-1, a simple area constriction served to let fuel and air into the combustion chamber but prevents exhaust gases from escaping from the inlet. Although Marconnet’s design couldn’t completely avoid the backflow at the inlet, the valveless pulsejet became one of the major areas in pulsejet research, and a few designs were patented.

The U-shaped Lockwood-Hiller engine (Lockwood, 1963; Lockwood & Patterson, 1964; Logan, 1951; Logan, 1949) is perhaps the most successful of the valveless designs. The inlet is bent backwards to change the flow direction and keep part
of the hot gas inside the tube. When the pressure in the combustion chamber is below atmospheric, the hot gases are pushed back into the combustion chamber and ignite the reactants. This design maximizes the net thrust.

Kentfield (1990) designed a pressure gain pulse-combustor that has a thrust augmentation device allowing cold air to be entrained by the hot gas from the pulsejet inlet, providing thrust augmentation. Because of the near constant-volume combustion, this valveless pulsejet system was designed to replace the traditional steady flow combustors in the gas turbines to increase gas turbine performance. According to his experiments, the pulse-combustor increased the maximum pressure gain from 1.6 to 4 percent of the compressor absolute delivery pressure.

The pulsejet is based on the Humphrey thermodynamic cycle, where isochoric heat addition (combustion) follows an isentropic compression and isobaric heat rejection follows an isentropic expansion. However, since the wave compression is weak, the thermodynamic efficiency is low, especially compared with the Brayton cycle where mechanical compression offers very high thermodynamic efficiency. This lack of thermodynamic efficiency is somewhat offset by the fundamental simplicity of the pulsejet. For typical large-scale applications, the pulsejet is not competitive, and interest in pulsejets has been relatively low for the past 40 years. However, the thermodynamic efficiency of conventional engines (such as gas turbines) decreases non-linearly with decreasing characteristic engine scale (Waitz et al., 1998; Spadaccini et al., 2003). Pulsejets, especially valveless pulsejets, are attractive as candidates for miniaturization due to their simple design, leading to the resurgence in interest in pulsejets.
It is expected that pulsejets may be more difficult to operate as their size decreases due to a smaller combustion chamber volume, insufficient mixing, and dissipation of the necessary pressure oscillations. The scalability is a function of the inlet length, area ratio between the inlet and the combustion chamber, and the exhaust duct length. It is not practical to test all the possible geometries with different parameter values, therefore CFX is used to simulate the operation of the pulsejet and provide a detailed understanding of the interacting chemical kinetic, fluid mechanic, and acoustic processes occurring in the small scale pulsejet.

2.2 Experimental Setup

The valveless pulsejet investigated in this research is a scaled down version of the BMS (Bailey Machining Service) hobby-scale pulsejet. As shown in Figure 2-2, the valveless pulsejet consists of three sections: the inlet, the combustion chamber (a constant-area section and a transition section), and the exhaust duct. Five ports were added to allow measurement of the pressure and temperature at various axial locations (they were placed 1.0, 2.0, 4.5, 8.8, and 14.0 cm from the beginning of the combustion chamber). These locations correspond to immediately after the location of direct fuel injection, just before the transition section, just after the transition section, halfway down the exhaust tube, and just before the exit plane, respectively. Figure 2-3 shows different inlet orientations. Unless specifically mentioned, pulsejet in this paper has a forward-facing inlet.

Different inlet area to exit area ratios (0.13, 0.09, and 0.04) and inlet lengths
(5.08, 3.81, 2.54, and 1.27 cm) were tested. Fuel was continuously injected into the combustion chamber and air entered the combustion chamber whenever the pressure was lower than the ambient pressure, i.e., the pulsejet was naturally aspirated. A mini spark plug was used to ignite the air-fuel mixture initially Figure 2-4. After several combustion events, fuel and air mixture was ignited by contact with the residual hot products in the pulsejet and the hot walls. Thus, the spark plug was only required to initiate the combustion during the first few cycles. All cases were running in an environment of 1 atm pressure and approximately 300 K temperature.

Both rotometers and mass flow meters were used to measure fuel flow rates. Air flow rates were not measured. Fast response pressure transducers were used to measure the instantaneous pressure. B-type thermocouples were used to measure average gas temperature inside the jet at various axial locations. Time resolved thrust was measured via a piezoelectric load cell. The load cell was exposed to shear loads in the direction of positive and negative thrust. The required preload was achieved by compressing the load cell between two aluminum plates.

### 2.3 Numerical Model

The current study models unsteady, three-dimensional, compressible, viscous flow with heat transfer, combustion, and radiation. The geometry and dimensions of the jet model used in computations exactly corresponds to that used in experiments; this enables direct comparison between experimental and numerical results and validation of computational results by our experiments. CFX5.7 software package was utilized. The
second order transient scheme and high-resolution advection scheme were used to capture the compression/expansion waves. The timestep was chosen such that the Courant number was unity and the solution had a convergence criterion of $10^{-4}$ in residual mean square value.

The computations were performed on the NC State IBM Blade center utilizing a single 3.0 GHz Inter Xeon processor. Typical computational time for one cycle of the pulsejet was 4.3 CPU hours. The turbulent flow was simulated using a $k$-$\varepsilon$ model based on the Reynolds Averaged Navier-Stokes (RANS) equations. The $k$-$\varepsilon$ model was validated by comparing the experimental data with simulation data for operation frequency, pressure, and average temperature. Previous work (Kiker et al., 2005) had shown that $k$-$\varepsilon$ model gives the smallest error in predicting jet operation frequency; for example, the error is within ±5% for a 50 cm valved pulsejet operating at a measured frequency of 232 Hz. The Westbrook-Dryer single-step reaction model with EDM was used to simulate the combustion process (Westbrook & Dryer, 1981). The viscous effect in the boundary layer region was modeled by the log-law, in which the empirical formulas were provided to connect the wall conditions to the dependent variables at the near-wall mesh node.

Governing equations for the fluid flow are given below. The continuity equation is:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{2-1}
\]

the momentum equation based on the eddy viscosity assumption and is given by
\[
\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = \nabla p' + \nabla \cdot [\mu_{\text{eff}} (\nabla \mathbf{U} + (\nabla \mathbf{U})^T)]
\]

(2-2)

where \( \mu_{\text{eff}} \) is the total viscosity that accounts for turbulent viscosity, and \( p' \) is the modified pressure given by

\[
p' = p + \frac{2}{3} \rho k
\]

(2-3)

The \( k-\varepsilon \) model is based on the eddy viscosity concept, which assumes:

\[
\mu_{\text{eff}} = \mu + \mu_t
\]

(2-4)

where \( \mu_t \) is the turbulent viscosity:

\[
\mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon}
\]

(2-5)

The \( k-\varepsilon \) model includes the following equations for the kinetic energy, \( k \), and the dissipation rate of turbulence, \( \varepsilon \):

\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{U} k) = \nabla \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon
\]

(2-6)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \mathbf{U} \varepsilon) = \nabla \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon)
\]

(2-7)

where \( C_{\varepsilon 1}, C_{\varepsilon 2}, \sigma_k, \) and \( \sigma_\varepsilon \) are model constants (their values are given in Table 2-1) and \( P_k \) is the turbulence production due to the viscous force:

\[
P_k = \mu_t \mathbf{U} \cdot (\nabla \mathbf{U} + (\nabla \mathbf{U})^T) - \frac{\varepsilon}{3} \mathbf{U} \cdot (3 \mu_t \nabla \cdot \mathbf{U} + \rho k)
\]

(2-8)

The energy equation is:
\[
\frac{\partial \rho (h + \frac{1}{2} U^2 + k)}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot [\rho \mathbf{U} (h + \frac{1}{2} U^2 + k)] = \nabla \cdot \left( \lambda \nabla T + \frac{\mu_t}{\text{Pr}_t} \nabla h \right) + S_f
\]  
(2-9)

The EDM, which was utilized to model the combustion, assumes that either reaction is fast compared to turbulent mixing (high Damköhler number is assumed), or reaction rate is proportional to the timescale of turbulent mixing. The timescale of turbulent mixing, which depends on the eddy properties, is determined as the ratio of \(k\) and \(\varepsilon\).

The reaction rate was determined from the minimum of expressions (2-10) and (2-11) below:

\[
R_k = A \frac{\varepsilon}{k} \min \left( \frac{[I]}{v_{KI}} \right)
\]  
(2-10)

\[
R_k = AB \frac{\varepsilon}{k} \left( \sum_p [I] W_i \right)
\]  
(2-11)

where \([I]\) is the molar concentration of the reactant I and \(P\) loops over all product components. \(A\) and \(B\) are model constants and their values are given in Table 2-1. Flame extinction was also modeled by controlling the chemical timescale and extinction temperature values. The local reaction rate was set to zero if the turbulent timescale was smaller than the chemical timescale specified. In this case the chemical timescale was 0.0004 second. The turbulence timescale is calculated from the flow field as \(k/\varepsilon\). The other method to determine the flame extinction is such that the flame is locally quenched whenever the temperature is less than the specified extinction temperature. Both the
chemical timescale and the extinction temperature were specified to model the flame extinction.

## 2.4 Results and Discussions

### 2.4.1 The Valveless Pulsejet Operation Cycle

To illustrate 15 cm valveless pulsejet operation cycle, Figure 2-5 displays simulation results for the jet of the total length of 20.5 cm and the inlet area to the combustion cross-section area ratio of 0.13 (see case 1.3 in Table 2-2). These simulation results are validated by comparison with experimental data, as shown later. The pulsejet is static and the wall temperature is 300 K. The pressure outside the pulsejet is atmospheric. Gas-phase hydrogen is injected into the combustion chamber with the same mass flow rate as in experiments. The operation cycle is separated into ten steps from (1) to (10) from top to bottom shown in Figure 2-5. The positive direction of velocity $u$ is defined as flow going out of the exit. For a better view of hydrogen distribution, the maximum value in the legend is set to 0.2.

1. **Combustion event occurs at the stoichiometric contour between air and hydrogen.**
   
   The pressure and temperature begin to increase in the combustion chamber. The negative velocity of the cold backflow air decreases. Air continues entering the combustion chamber through the inlet, but with reduced velocity.

2. **Combustion continues causing the pressure and temperature to increase in the combustion chamber.** Compression waves are generated and propagate to the inlet and the exit. When the pressure of the cold air becomes equal to the pressure
of the hot gases, the velocity goes to zero at the interface of these two gases.

(3) Expansion waves are generated at the inlet and decrease pressure in the combustion chamber. A positive, increasing velocity characterizes the flow at the exit; while at the inlet, the hot products flow out with an increasing negative velocity.

(4) Expansion waves are generated at the exit and travel back to the combustion chamber. Pressure decreases in the combustion chamber and the velocity of the gases out of the inlet and the exit reach their maximum. Most of the hydrogen is oxidized by the time.

(5) The pressure in the combustion chamber keeps decreasing. Temperature increases in the inlet.

(6) The expansion waves from the exit enter the combustion chamber and further decrease the pressure in the combustion chamber. The outgoing velocity at the inlet starts to decrease.

(7) The expansion wave enters the combustion chamber and decreases the pressure below the atmospheric. Air enters the combustion chamber through the injection. Hot products continue to be expelled at the outlet but with a lower velocity.

(8) The pressure and temperature in the combustion chamber continue decreasing while the inlet velocity continues increasing. The product velocity at the exit goes to zero and actually reverses, causing backflow at the exit, resulting in a temperature decrease due to entrainment of ambient air at 300 K.

(9) Cold air from the inlet enters the combustion chamber. Hot gas in the exhaust
duct is pushed back to the combustion chamber. The pressure in the combustion chamber increases.

Backflow continues, but its negative velocity becomes smaller. When the pressure in the combustion chamber approaches atmospheric pressure and air from the inlet mixes with hydrogen in the combustion chamber, the next cycle begins.

In each cycle, the combustion chamber pressure is decreased by the expansion waves from both the outlet and the inlet. Compared with the valved designs, this does not provide lower sub-atmosphere pressure in the combustion chamber due to the mass addition of the air from the inlet. The exhaust duct may contain hot gases generated by several combustion events. The cold air entering the combustion chamber creates a strong vortex that greatly accelerates the mixing process. The oxygen that reacts with hydrogen enters the combustion chamber from the inlet only; no fresh air enters the combustion chamber through the exhaust duct. From these numerical results, it is evident that the inlet design is critical to the valveless pulsejet operation, justifying the need to investigate the geometric influence of the inlet on small scale pulsejets.

2.4.2 Experimental Scalability Study

In this paper, scalability is studied by varying the inlet length, inlet inner diameter, and exhaust duct length to find the range of pulsejet lengths in which the pulsejet can be operated. Different exit geometries were also examined. For each case, the inlet to combustion chamber area ratio was held constant while varying inlet and
exhaust duct lengths. For each inlet length, pulsejet operation was attempted at several exhaust lengths using identical incremental steps for each case. The results are shown in Table 2-2. \( A_i \) and \( A_c \) in Table 2-2 denote the areas of the inlet and combustion chamber cross-sections, respectively. Table 2-2 shows that, within the tested dimension range, decreasing the inlet length increases the pulsejet scalability regardless of the area ratio.

### 2.4.2.1 Length Investigation

Table 2-3 tabulates the shortest pulsejet lengths, per inlet configuration, that were able to achieve self-sustaining combustion. It is evident that, for a given intake area, the minimum feasible length decreases with decreasing inlet length. In other words, the jet with a shorter inlet has a wider operation range. However, for a given inlet length changing the inlet area does not have much effect on jet scalability. Table 2-3 shows that the minimum operation length is a stronger function of inlet length rather than inlet area ratio; suggesting that area ratios may only be utilized to slightly reduce inherent inlet to exhaust duct length ratios.

Minimal jet lengths are plotted in Figure 2-6 against inlet length to exit length ratios in order to investigate trends in behavior. The inlet length is denoted as \( L_i \), the exhaust duct length is denoted as \( L_e \), and the minimum overall jet length is denoted as \( L_{\text{min}} \). \( AR \) is the area ratio of the inlet to that of the combustion chamber. For a fixed inlet length ratio the minimum feasible pulsejet length does not change much regardless of the \( AR \). A linear increase of the minimum inlet length is observed with increasing \( L_i / L_e \). This indicates that for a certain combustion chamber diameter, there is a critical inlet
length ratio for which the pulsejet will remain self-sustaining. Inlet length ratios have actually been shown to have a significant effect on maximum hydrogen flow rates at various inlet configurations, as shown in Table 2-4.

2.4.2.2 Pulsejet Frequency

With forced air, the pulsejet can operate over a fairly wide range of conditions. However, independent operation is much more restrictive and a function of many parameters. Figure 2-7 displays the effect of changing the overall jet length on the frequency, for a fixed $AR$ value of 0.04. Similar to valved pulsejets, the frequency of valveless pulsejets decreases with increasing the total length. Furthermore, increasing the inlet length also decreases the frequency. This is because the increased inlet length increases the minimum feasible jet length, as shown above. Thus, the total jet length also increases, which decreases the frequency. This phenomenon is also observed in experiments with different $AR$ values.

Figure 2-8 shows how $AR$ affects frequency with a fixed inlet length. It is evident that increasing the inlet area leads to increasing the frequency of the valveless pulsejet. The pulsejet with larger inlet area operates for larger length ranges.

2.4.3 Fuel Flow Investigation

As shown in Table 2-4, where configuration A denotes a constant exhaust length at 38 cm and configuration B denotes the minimum exhaust duct length to achieve successful operation, the larger the $AR$, the higher the maximum fuel flow rate, and hence throttleability. At the smallest $AR$ of 0.04, the maximum fuel flow rate is the lowest and
is relatively insensitive to either inlet length or exhaust duct length. For other AR’s, the fixed exhaust duct length (A) typically has a lower $\dot{m}_{f,\text{max}}$ than for case B. The highest $\dot{m}_{f,\text{max}}$ tend to occur with the two intermediate length inlets.

Case B, which has the minimum exhaust duct length, has a larger throttleability range. This can be explained by the accompanying increase in operating frequency associated with a decrease in total length. If higher frequencies permit more combustion events per minute, then a higher fuel consumption rate may be related to a decrease in total jet length.

### 2.4.4 Comparison between the Simulations and the Experiments

To validate the CFX code, two simulations were conducted and the results were compared with experimental data. Figure 2-9 (a) shows the experimental result of the case 1.3 in Table 2-2 with a 22.5 cm total length. Chamber pressure (port 2) generally remained in the $\pm 0.02$MPa range, while thrust is in the $\pm 2.0$ N range. The frequency is 1010 Hz and the mean temperature in the combustion chamber is 1550 K. Figure 2-9 (b) is the result of case 1.3 with a 34.3 cm total length. The chamber pressure generally remained in the $\pm 0.02$MPa range, while thrust decreased to $\pm 1.2$ N. The operation frequency is 830 Hz and the mean temperature in the combustion chamber is 1520 K.

The corresponding simulation results are shown in Figure 2-10. The simulation domain contains approximately 40,000 elements. The turbulence was modeled using the $k-\varepsilon$ model and the Eddy Dissipation Model was used for the combustion. Static thrust was calculated by summing the thrusts generated at both the inlet and the outlet.
At each end, only momentum thrust was calculated since the pressure
difference to the ambient pressure is negligible. The average mass flow rate of hydrogen
was 0.016 g/s, which was the same as in experiments.

The simulated pressure is in the ±0.02 Mpa range correspondent to the
experimental results and thrust is in the ±0.8 N for the 22.5-cm jet and ±1N for the 34.3-
cm jet. The operation frequency for Figure 2-10(a) is 1,080 Hz and 806 Hz for Figure
2-10(b). The assumption that pressure at both the inlet and the exhaust duct ends is
exactly atmospheric may cause some inaccuracy in predicting thrust. The error in
predicting frequency is 7% for the 22.5 cm jet and 3% for the 34.3 cm jet. Also notable
is the ability of the model to capture the complex structure of the pressure oscillations. In
Figure 2-9(a) and Figure 2-10(a), it is clear that the pressure is not exactly sinusoidal.
There is a component at the same frequency but slightly offset in time as the decreasing
pressure side of the oscillation. In Figure 2-9(b) and Figure 2-10(b), the offset is nearly
180 degrees and this secondary oscillation is very clear.

2.4.5 Inlet Orientation

Three different valveless inlet orientations were also investigated to maximize net
thrust (Schoen, 2005). Pulsejet operation was achieved with a 90 degrees orientated inlet
(Figure 2-3, configuration a) at a 0.04 inlet area ratio. For an inlet length of 2 cm,
pulsejet operation was achieved at a minimum jet length of 25.2 cm. Fuel flow rate was
limited within the range of 0.017 g/s to 0.023 g/s. A maximum overall length of 33.7 cm
was found successful for the 90-degree configuration. At the longer length, the throttle
ability limits increased to between 0.014 g/s and 0.025 g/s.

In addition, tests were performed with an inlet orientated 135 degrees (Figure 2-3, configuration b), perpendicular with the slope of the transition section. An inlet area ratio of 0.04 was tested at jet lengths of 50.0, 33.6, 25.2, and 22.5 cm. The inlet was approximately 0.7 cm long. All lengths allowed pulsejet operation except for the shortest length of 22.5 cm. At 25.2 cm, the pulsejet was difficult to start and was only operable for a number of seconds at a fuel flow rate of about 0.014 g/s before cutting out.

To study reverse inlet operation, whereabouts thrust is conserved by directing inlet and exit momentum in the same direction, a new jet design was developed. As Figure 2-4 illustrates, a single steel 'combustion cylinder' component replaced both the combustion chamber and transition sections of the conventional scaled down BMS jet.

Three holes were drilled in the opposing face of the combustion cylinder to create inlets that faced 180 degrees (Figure 2-3, configuration c) from the conventional valveless inlet position. The inlet lengths were approximately 0.89 cm long each and the collective inlet area ratio was 0.04. Pressure and temperature were simultaneously recorded for a jet length of 37.5 cm and the results are plotted in Figure 2-11. Compared with the pressure profiles measured in the conventional valveless pulsejets, there is a secondary pressure rise in each cycle of the reverse-facing inlets. This is probably caused by the compression wave being reflected from the left wall of the combustion chamber.
2.5 Conclusions

In order to ascertain the scalability characteristics of the valveless pulsejet engine, it is necessary to first investigate the viability of operation under a range of configurations for an individual class of engine sizes. Investigation of the 15 cm class valveless pulsejet is a vital stepping stone to bridge the gap between micro-scaled pulsejet engines and the hobby-scaled engines. This research classifies the physical effects of pulsejet geometries on engine performance. To determine characteristics of performance, the chamber pressure and temperature, thrust, and operation frequency were measured. Numerical simulations are used to provide a detailed understanding of the flow behavior in the valveless pulsejet cycle. The simulation results are validated by the experimental results. This study is unique in that it represents the first detailed investigation of a valveless pulsejet engine in this size class, the smallest size known running up to date. The relevant conclusions drawn from this work are as follows:

1. The numerical model, validated by the experimental results, shows:
   
a. The expansion waves from the outlet are able to enter the combustion chamber before the next cycle.

   b. In each cycle, the combustion chamber pressure is decreased by the expansion waves from the outlet and the inlet as well. The backflow from the exhaust duct cannot travel to the combustion chamber, and the oxygen for the reaction is provided by the airflow from the inlet only.

   c. The exhaust duct may contain hot gases generated by several successive combustion events. This behavior is not observed in the valved pulsejet. The
cold air entering the combustion chamber creates a strong vortex that greatly accelerates the mixing process.

2. Exhaust duct length and inlet length are directly coupled in the valveless pulsejet.
   a. Pulsejet operation at minimum overall lengths was achieved with the shortest inlet lengths.
   b. Pulsejet operation at longer jet lengths was achieved with longer inlet lengths and smaller inlet area ratios.
   c. Maximum exhaust duct lengths exist for corresponding inlet lengths and area ratios. Results suggest that for given a valveless configuration, there exists a critical length above which pulsejet operation cannot be achieved.

3. Minimum exhaust duct length can be further reduced (from a constant area geometry) by about 16% on average with the addition of a diverging exit nozzle.

4. Pulsejet operation was achieved from 90º, 135º, and 180º inlet orientations with respect to the conventional forward facing valveless design.

5. Preliminary tests indicate that valveless pulsejets with multiple opposed facing inlets present similar behavioral characteristics as those of conventional design. It also may be concluded that the consolidated inlet area ratio of multiple inlets is comparable to that of a single rearward-facing inlet, taking into consideration inlet placement and internal direction of inlet flow.

6. The two main parameters determining the success of a pulsejet to operate are chemical kinetic time versus jet length and inlet area to combustor area ratio. At shorter lengths, the chemical kinetic reaction rate (combustion time) becomes
challenged by the period of fluid mechanic oscillations. This would explain why fuels with longer chemical time scales such as propane did not permit pulsejet operation in smaller jet sizes.
Table 2-1 Values of various model constants used in simulations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Eddy dissipation model coefficient</td>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td>B</td>
<td>Eddy dissipation model coefficient</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>$C_{e1}$</td>
<td>$k$-$\varepsilon$ turbulence model constant</td>
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<td>1.44</td>
</tr>
<tr>
<td>$C_{e2}$</td>
<td>$k$-$\varepsilon$ turbulence model constant</td>
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<td>1.92</td>
</tr>
<tr>
<td>$\sigma_k$</td>
<td>Turbulent model constant for the $k$ equation</td>
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<td>1.0</td>
</tr>
<tr>
<td>$\sigma_\varepsilon$</td>
<td>$k$-$\varepsilon$ turbulence model constant</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>$k$-$\varepsilon$ turbulence model constant</td>
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<td>0.09</td>
</tr>
</tbody>
</table>

Table 2-2 Experimental results for the scalability study

<table>
<thead>
<tr>
<th>Case</th>
<th>$AR$</th>
<th>Inlet length</th>
<th>Exhaust duct lengths at which self-sustained combustion was achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(A_i/A_c)$</td>
<td>$L_i$ (cm)</td>
<td>$L$ (cm)</td>
</tr>
<tr>
<td>1.1</td>
<td>0.13</td>
<td>5.08</td>
<td>N/A</td>
</tr>
<tr>
<td>1.2</td>
<td>0.13</td>
<td>3.81</td>
<td>45.7, 29.2</td>
</tr>
<tr>
<td>1.3</td>
<td>0.13</td>
<td>2.54</td>
<td>44.5, 39.1, 33.7, 28.3</td>
</tr>
<tr>
<td>1.4</td>
<td>0.13</td>
<td>1.27</td>
<td>42.9, 37.5, 32.1, 26.7, 21.3, 15.9</td>
</tr>
<tr>
<td>2.1</td>
<td>0.09</td>
<td>5.08</td>
<td>41.2, 36.2</td>
</tr>
<tr>
<td>2.2</td>
<td>0.09</td>
<td>3.81</td>
<td>45.7, 34.9, 23.8</td>
</tr>
<tr>
<td>2.3</td>
<td>0.09</td>
<td>2.54</td>
<td>44.1, 33.0, 22.5</td>
</tr>
<tr>
<td>2.4</td>
<td>0.09</td>
<td>1.27</td>
<td>42.9, 31.8, 21.3, 15.6</td>
</tr>
<tr>
<td>3.1</td>
<td>0.04</td>
<td>5.08</td>
<td>47.0, 36.2</td>
</tr>
<tr>
<td>3.2</td>
<td>0.04</td>
<td>3.81</td>
<td>45.7, 34.6, 29.5</td>
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<tr>
<td>3.3</td>
<td>0.04</td>
<td>2.54</td>
<td>44.3, 33.3, 22.5</td>
</tr>
<tr>
<td>3.4</td>
<td>0.04</td>
<td>1.27</td>
<td>42.9, 32.1, 21.3, 15.9</td>
</tr>
</tbody>
</table>
Table 2-3 Minimum feasible pulsejet lengths for corresponding inlet configurations.

<table>
<thead>
<tr>
<th>Inlet Length, ( L_i ) (cm)</th>
<th>( AR ) 0.13</th>
<th>0.09</th>
<th>0.04</th>
</tr>
</thead>
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<tr>
<td>1.27</td>
<td>15.86</td>
<td>15.56</td>
<td>15.86</td>
</tr>
<tr>
<td>2.54</td>
<td>22.54</td>
<td>18.10</td>
<td>18.42</td>
</tr>
<tr>
<td>3.81</td>
<td>24.77</td>
<td>19.69</td>
<td>25.40</td>
</tr>
<tr>
<td>5.08</td>
<td>31.15</td>
<td>31.43</td>
<td>32.07</td>
</tr>
</tbody>
</table>

Table 2-4 Maximum \( \text{H}_2 \) flow rates at various inlet configurations. A. For a constant exhaust duct length of 38.1 cm. B. For minimum feasible pulsejet lengths. All measurements are in g/s.

<table>
<thead>
<tr>
<th>Inlet Length, ( L_i ) (cm)</th>
<th>( AR ) 0.13</th>
<th>0.09</th>
<th>0.04</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>0.067</td>
<td>0.038</td>
<td>0.012</td>
</tr>
<tr>
<td>( B )</td>
<td>0.067</td>
<td>0.049</td>
<td>0.013</td>
</tr>
<tr>
<td>( A )</td>
<td>0.035</td>
<td>0.023</td>
<td>0.012</td>
</tr>
<tr>
<td>( B )</td>
<td>0.083</td>
<td>0.057</td>
<td>0.023</td>
</tr>
<tr>
<td>( A )</td>
<td>0.034</td>
<td>0.030</td>
<td>0.012</td>
</tr>
<tr>
<td>( B )</td>
<td>0.076</td>
<td>0.052</td>
<td>0.012</td>
</tr>
<tr>
<td>( A )</td>
<td>0.033</td>
<td>0.026</td>
<td>0.012</td>
</tr>
<tr>
<td>( B )</td>
<td>0.060</td>
<td>0.034</td>
<td>0.013</td>
</tr>
</tbody>
</table>
Figure 2-1 Marconnet’s design with the aerodynamic valve

Figure 2-2 15 cm valveless pulsejet geometry and dimension (cm)
Figure 2-3 The inlet orientations a) 90-degree b) 135-degree c) 180-degree

Figure 2-4 The combustion cylinder components
Figure 2-5 Simulation results for pressure and temperature: a) Pressure b) Temperature c) Velocity u d) Hydrogen mass fraction.
Figure 2-6 Minimum feasible pulsejet lengths versus inlet to exit length ratios.
Figure 2-7 Frequency versus pulsejet length for a 0.04 inlet area ratio.

Figure 2-8 15 cm pulsejet operation frequency versus total length for different inlet area ratios, $L_i = 2.54$ cm.
Figure 2-9 Experimentally measured pressure at port 2 and thrust for an area ratio of 0.13 and 2.54 cm inlet (a) 22.5 cm total length (b) 34.3 cm total length.
Figure 2-10 Simulation results of pressure at port 2 and thrust for an area ratio of 0.13 and 2.54 cm inlet (a) 22.5 cm total length (b) 34.3 cm total length.
Operation frequency: 590 Hz
Mean temperature: 1460 K

Figure 2-11 Pulsejet combustion chamber pressure for an opposed-facing inlet configuration with a 0.04 collective area ratio.
3 Experimental and Numerical Investigation of an 8-centimeter Valveless Pulsejet

3.1 Introduction

The pulsejet is one of the simplest propulsion devices, requiring no turbomachinery, or moving parts in some cases. The pulsejet was originally conceived in the early 1900’s and developed into a successful propulsion system by the Germans in WWII for the V-1 ‘buzz bomb’, the name being derived from the impressive acoustic emission at 50 Hz from these engines. Their simple structure and light weight make them an ideal thrust-generation device, but their thermodynamic efficiency is low compared to gas turbine engines due to the lack of mechanical compression, which results in low peak pressure. Due to this low efficiency, the pulsejet received little attention after the late 1950’s. However, pulsejets with no moving parts may be advantageous for building smaller propulsion devices. The thermodynamic efficiency of conventional engines (such as gas turbines and both SI and CI IC engines) decreases non-linearly with decreasing characteristic engine length scale. Also, small scale engines with moving parts are more prone to breakdown due to fatigue of the moving components (Majumdar & Tien, 1998). Pulsejets, especially valveless pulsejets, are attractive as candidates for miniaturization due to their extremely simple design.

The general pulsejet cycle (forward-facing inlet) can be illustrated as follows. The combustion event begins when the combustion chamber pressure is above atmospheric and the temperature of the fuel/air mixture increases, due to mixing with
residual products, to the auto-ignition temperature. A compression wave is generated and combustion increases both temperature and pressure in the combustion chamber, driving the flow toward the exit and inlet at gradually increasing velocity. The relatively short combustion event ends and when the compression wave reaches either the pulsejet inlet or the exit, an expansion wave is generated due to overexpansion and travels back into the combustion chamber. Flow velocity reaches its positive maximum at the exit at this time. The expansion wave decreases the pressure in the exhaust tube and the combustion chamber to sub-atmosphere, resulting in backflow at both the inlet and exit. The next charge of fuel/air mixture enters into the chamber due to this backflow at the inlet. The mass addition increases the combustion chamber pressure. When the pressure in the combustion chamber approaches the atmosphere pressure, the next cycle begins.

One of the most significant and technically challenging aspects of the micro-propulsion device is its limited residence time. Once the combustion chamber size becomes 2 to 3 orders of magnitude smaller than that of a large scale jet engine, the residence time within the combustion chamber approaches the characteristic chemical kinetic time scale for hydrocarbon-air reactions (Waitz et al., 1998). The chemical time scale can be shortened by using hydrogen as fuel, which was necessary in this work. It may even be necessary to premix and preheat the fuel and air to decrease the chemical kinetic time scale. It has also been suggested that increasing the combustion chamber size relative to the engine size will help with the very short residence times (Spadaccini et al., 2003). In a review paper, Roy et al. (2004) reported the typical length for a pulse detonation engine is 0.3-3 m. We believe this 8 cm pulsejet is the smallest operational
pulsejet reported (Grossman & Lottati, 1991; Fan et al., 2003; Bussing & Pappas, 1994; Kailasanath, 2002). The fuel injection system, combustion chamber, and the inlet geometry must be carefully designed to create a fast mixing process and the necessary fluid dynamic and acoustic time scales to permit pulsejet operation.

Another challenge is the heat loss to the walls due to the high surface-area-to-volume ratio. Large thermal losses have a direct impact on overall combustor efficiency and they can increase kinetic times and narrow flammability limits through suppression of the reaction temperatures (Spadaccini et al., 2003). For the oscillating combustion process to be self-sustaining, excessive heat loss, which lowers the temperature of the walls and the residual gas, must be prevented.

3.2 Experimental Setup

Hobby scale pulsejets on the order of 50 cm total length have been used for many years for RC aircraft and hydroplane propulsion applications. This hobby scale version is typically run in a valved mode, with petal valves opening on the low pressure ingestion stroke and closing as the pressure increases due to heat release from combustion.

Previously, a 15 cm total length pulsejet was investigated numerically and experimentally (Geng et al., 2007). In the 15 cm version, the traditional valved inlet was replaced with a valveless inlet. Attempts to design and build a valved 15 cm pulsejet were unsuccessful due to the reed valves, which were directly scaled down from the 50 cm valves. Furthermore, the reed valves can be easily damaged in the operation of the pulsejet. Thus, we choose valveless designs for both the 15 cm and 8 cm pulsejets. With
the valveless inlets, the inlet cross-sectional area and length were important parameters in determining operability. The current design is based on the 15 cm pulsejets; all dimensions are scaled by half except for the combustion chamber diameter, which is the same as that of the 15 cm pulsejet.

The fuel used in all results reported here was hydrogen. As opposed to the large valved inlets which use a liquid fuel atomized upstream of the combustion chamber in a venture and thus only enters the combustion chamber with a fresh charge of air, fuel was injected at a constant rate directly into the combustion chamber. This greatly simplified the fuel injection process and eliminated the need for pulsed injection. The air inflow was still controlled by the oscillating pressure and acoustic waves.

Two types of inlets were tested: a forward-facing inlet configuration and a rearward-facing inlet configuration as shown in Figure 3-1 (a) and Figure 3-1 (b), respectively. The spark igniter can be seen at the top of the pulsejet shown in Figure 3-1 (b), and the fuel injection port is 90 degrees from the igniter. Figure 3-2 shows a schematic of the experimental apparatus for a rearward-facing inlet configuration. The combustion chamber was threaded to allow variation in combustion chamber volume, and the exhaust duct was threaded to allow extensions to be added. It was observed in both the 15 and 50 cm pulsejets that the forward-facing configuration generates very little net thrust because hot products are expelled through the inlet as well as the exhaust duct. To improve the net thrust performance, two rearward-facing inlets were designed and screwed into the area-transition section of the pulsejet, and the forward-facing inlet was replaced with a solid disk. The combined cross-sectional area of the two inlets was equal
to that of the single forward-facing inlet, yielding a rearward inlet diameter of 0.22 cm.

Mass flow meters were used to measure the fuel flow rate while the air flow rate was not measured (naturally aspirated). Fast response pressure transducers were used to measure the instantaneous pressure and B-type thermocouples were used to measure average gas temperature inside the jet at various axial locations. Time resolved thrust was measured via a piezoelectric load cell. The load cell was exposed to shear loads in the directions of positive and negative thrust, with the required preload being achieved by compressing the load cell between two aluminum plates.

### 3.3 Numerical Model

The current study models the unsteady, three-dimensional, compressible, viscous flow with heat transfer and radiation, utilizing the CFX5.7 commercial software package. A second order transient scheme and high-resolution advection scheme were used to capture the compression/expansion waves. Governing equations for the fluid flow are given in previous work (Geng et al., 2007).

The computations were performed on a single 3.0 GHz Intel Xeon processor, with typical computational time for one cycle of the pulsejet being 20 CPU hours. The turbulent flow was simulated using a k-ε model based on the Reynolds Averaged Navier-Stokes (RANS) equations. The Westbrook-Dryer single-step reaction model with EDM was used to simulate the combustion process. The viscous effect in the boundary layer region was modeled by the log-law, in which empirical formulas were provided to connect the wall conditions to the dependent variables at the near-wall mesh node.
The pulsating flow at the pulsejet inlet and exit made it challenging to impose the boundary conditions. The flow temperature at both the exit and inlet, for example, is some average temperature of the mixture of the hot exhaust gas and cold ambient air. To fully capture the intake and exhaust phases, the flow fields outside the inlet and the exit were also modeled. Neglecting the flow field near the inlet and exit and imposing boundary conditions at the inlet and exit plane lead to an artificially high operating frequency. As shown in Figure 3-3 for the rearward-facing inlet, two cylindrically-shaped computational domains were attached to the exit plane of the two inlets and were 0.5 cm in diameter and 2.54 cm (11.5 diameters) long. The domain attached to the exhaust duct was 3.0 cm in diameter and 7.62 cm (17 diameters) long. The boundary conditions at the cylinder boundaries were specified as one atmosphere absolute pressure and 300 K temperature. The whole domain contained 28,396 nodes and 95,489 elements. The computational time for this geometry was about 24 CPU hours per cycle.

The heat transfer process for the 8 cm pulsejet is important due to the high surface-area-to-volume ratio. Heat losses may affect the pressure rise, flame temperature, and operating frequency. Therefore, wall heat transfer process was modeled by specifying an average value of the heat transfer coefficient at different regions of the wall, which were obtained by solving a steady-state conjugate heat transfer problem. In this steady-state simulation, the wall heat transfer coefficient values were different on the inner and outer wall surfaces. The inner wall heat transfer coefficient was obtained and used in the current model in which the wall thickness was neglected to reduce the computational time. The temperature outside the pulsejet was assumed to be 300 K.
3.4 Results and Discussions

From the computational results, the pulsejet cycle can be described by the following 10 steps:

(1) Combustion event begins when hydrogen and air mix and are brought to their auto-ignition temperature through mixing with residual hot products from the previous cycle. The pressure and temperature begin to increase in the combustion chamber. Air continues entering the combustion chamber through the inlet with reduced velocity.

(2) Combustion continues, and peak pressure and temperature are reached in the combustion chamber. Compression waves are generated and propagate into the inlet and the exhaust tube. When the pressure of the hot gases becomes equal to the pressure of the cold air, the velocity goes to zero at the interface of these two gases.

(3) Expansion waves are generated at the inlet and decrease pressure in the combustion chamber. A positive, increasing velocity characterizes the flow at the exhaust duct exit; while at the inlet, the hot products are expelled with an increasing (negative) velocity.

(4) Expansion waves are generated at the exhaust duct exit and travel back to the combustion chamber. Pressure decreases in the combustion chamber and the gas velocity out of the inlet and the exit reach their maximum. Most of hydrogen is burned by this stage.

(5) The pressure in the combustion chamber continues decreasing. Temperature
increases in the inlet.

(6) Expansion waves from the exit enter the combustion chamber and further decrease the pressure in the combustion chamber. The outgoing (negative) velocity at the inlet decreases to zero.

(7) The combustion chamber pressure decreases below atmospheric, causing air to enter the combustion chamber through the inlet. Hot products continue to be expelled from the exhaust duct exit but the velocity continuously decreases.

(8) The pressure and temperature in the combustion chamber continue decreasing while the inlet velocity continues increasing. The product velocity at the exhaust duct exit goes to zero and then actually reverses. This backflow causes a temperature drop due to entrainment of ambient air up the exhaust duct.

(9) Cold air from the inlet continually enters the combustion chamber. Hot gas in the exhaust duct is pushed back to the combustion chamber. The pressure in the combustion chamber continues to increase.

(10) Backflow continues, but its negative velocity becomes smaller. When the pressure in the combustion chamber approaches atmospheric pressure and air from the inlet mixes with hydrogen in the combustion chamber, the next cycle begins.

It was observed in the simulations that chemical reaction consumes most of the oxygen in the combustion chamber. The oxygen that is needed for the combustion comes from the inlet only. The inlet design determines the amount of air entering the combustion chamber and thus plays a significant role in valveless pulsejet performance.
3.4.1 Operating frequency

One of the earliest descriptions of the pulsejet is that it behaves like a ¼ wave tube, or organ pipe (Tsien, 1946). Thus the fundamental operating frequency of the pulsejet is inversely proportional to the total pulsejet length, L. However from purely acoustic considerations, it is not clear how the operation frequency for the valveless pulsejet varies with the inlet length.

Four different inlet lengths (0.64, 0.9, 1.27, and 1.9 cm) were manufactured and tested in the rearward configuration to investigate the relation between the operating frequency and the inlet length. It should be noted that 0.64 and 1.9 cm represent the limiting inlet lengths at which the pulsejet will operate.

Instantaneous pressure measurements in the combustion chamber, shown in Figure 3-4 (a-b), reveal a slight change in operating frequency at these two limits. For these measurements, the fuel flow rate was held constant at 9 mg/s. The pressure oscillations were sinusoidal and were of low amplitude due to the valveless design. It can be seen that the average pressure in the combustion chamber is just above atmospheric. Figure 3-4 (a), which corresponds to an inlet length of 0.64 cm, yields an operating frequency of 1200 Hz, while the 1.9 cm inlet yields a frequency of 950 Hz. Similar to the effect of overall length variation, increasing the inlet length in the rearward configuration decreases the operating frequency of the jet. In comparing these two pressure profiles, it is clear that a secondary pressure oscillating at twice the frequency is occurring with the shorter inlet, but is nearly absent with the longer inlet. This small pressure rise is most likely caused by the compression wave being reflected back from the inlet.
Figure 3-5 shows how the operating frequency and combustion chamber peak pressure, both measured and computed, change over the entire range of inlet lengths. Based on these experimental data, the operating frequency was observed to scale with the inlet length \((L_{\text{inlet}})\) raised to negative 0.22 power. Considering the variation in the total length, \(L\), the relation may be modified as:

\[
f \propto \frac{1}{L} \cdot \left(\frac{1}{L_{\text{inlet}}}\right)^{0.22}
\]  

(3-1)

Figure 3-5 also shows that peak pressure increases with increasing inlet length. This is due to the fact that longer inlets cause greater difficulties for the hot products to exhaust through the inlet. Thus, the pressure rise in the combustion chamber is higher.

3.4.2 Peak combustion chamber pressure

In this paper, peak pressure is used as an engine performance metric. The majority of the tests with the forward-facing inlet pulsejet were conducted at a continuous fuel flow rate, \(\dot{m}_f\), of 9 mg/s of hydrogen. However, the pulsejet will operate over a rather large range of fuel flow rates. This particular pulsejet will operate with fuel flows as low as 3 mg/s and as high as 12 mg/s of hydrogen. At \(\dot{m}_f\) values beyond these limits, the jet extinguishes itself and can no longer sustain its operation.

Figure 3-6 shows how the pulsejet’s instantaneous combustion chamber pressure responds to changes in \(\dot{m}_f\). At 3 mg/s, the pulsejet is barely operating in the pulsejet mode, as is indicated by a very small pressure rise. Also, a higher frequency event was clearly observed at the low end of the \(\dot{m}_f\) range. As \(\dot{m}_f\) is increased, the secondary
pressure spike decreases in magnitude, and is barely detectable when \( \dot{m}_f \) is 10 mg/s.

The operating frequency of the jet varies with fuel flow rate only at the low end. Once \( \dot{m}_f \) reaches 6 mg/s, the frequency of the pulsejet remains relatively constant. This can be observed audibly as well: when the pulsejet first starts at the lowest fuel setting, it sounds slightly different than the high-pitched hum that accompanies the jet at full throttle.

Figure 3-7 shows a summary of experiments conducted comparing the jet’s behavior at various \( \dot{m}_f \). Based solely on these pressure traces, it is assumed that the jet operates most efficiently at the point of highest frequency and peak pressure—somewhere between 7 and 10 mg/s for the forward-facing inlet.

In contrast to the forward-facing inlet, the throttleability of the pulsejet changes considerably when the jet is operating in the rearward configuration (Figure 3-1). The operating range of the jet lies roughly between 6 mg/s and 9 mg/s of hydrogen. The jet will not start outside these \( \dot{m}_f \) values, and varying \( \dot{m}_f \) outside these values once the jet has started results in the jet cutting off. This decrease in throttleability is most likely the result of poor mixing conditions for the rearward-facing inlets. The pulsejet is able to ingest a much wider range of air flow in the forward-facing configuration, enabling the pulsejet to operate over a wider range of \( \dot{m}_f \).

Figure 3-8 shows a summary of the pressure traces of the pulsejet in the rearward configuration at various \( \dot{m}_f \). As with the forward-facing configuration, the frequency steadily increases with increasing \( \dot{m}_f \). This can be observed audibly in the experiments.
In contrast to Figure 3-7 the peak pressure rise shown in Figure 3-8 quickly reaches a steady value as the fuel flow rate is increased. The rearward inlet configuration does not allow the pulsejet to breathe as easily, thus the pulsejet shuts off at a lower fuel setting.

3.4.3 Net thrust and specific fuel consumption

It was demonstrated through exhaust velocity measurements in the 50 cm pulsejet that the exhaust cycles between positive and negative velocities in a sinusoidal fashion (Kiker et al., 2005). This negative exit velocity results in negative thrust for some portion of the oscillating period. Thus, time-resolved thrust measurements were desirable to investigate how the pulsejet’s thrust is coupled to combustion chamber pressure.

In the forward-facing configuration, it was expected that the resultant net thrust should be very small due to the expelling of combustion products in the forward direction. Figure 3-9 shows the time-resolved thrust of the 8 cm pulsejet in the forward-facing inlet configuration. It can be seen from this figure that the average thrust is indeed very small. The thrust oscillation frequency appears to be double that of the pressure trace, although this may be an artifact of the thrust stand, whose natural frequency was only a factor of three higher. As the pressure begins to fall below atmospheric, the pulsejet appears to produce a sudden burst of positive thrust.

In the rearward configuration, all of the products from the combustion chamber are being expelled in the same direction. During the sub-atmospheric air ingestion phase, the momentum flux occurs in the opposite direction and produces a negative thrust component. However, this component is small when compared with the positive component of the exhaust flow due to its much lower velocity.
Figure 3-10 shows the time history of the pulsejet’s thrust in the rearward inlet configuration. The thrust curve has an average thrust of 0.95 N (the threshold of the load cell is +/- 0.005 N), yielding a thrust specific fuel consumption of 0.02 kg/N-hr. Similar to that of the forward-facing configuration, the thrust measurements are at a frequency that is twice that of the pressure trace. However, no negative thrust was observed in the rearward inlet configuration.

3.5 Conclusions

Small-scale pulsejets may be good candidates for micro propulsion devices due to their simple designs. A combined experimental and numerical approach was used to investigate the performance of a hydrogen fueled 8 cm valveless pulsejet with two inlet configurations: forward-facing and rearward-facing. To the author’s knowledge, this is the smallest operational pulsejet reported. This work showed that:

1. The simulation provided physical insight into the pulsejet operation. The simulated operation frequency and peak pressure matched with experimental data. It was observed that for each operational cycle, combustion consumes most of the oxygen in the combustion chamber, and the oxygen comes from the inlet only. Acoustics and fluid mechanics are both important in determining the operating characteristics of these engines.

2. In the traditional valved inlet, the operating frequency is solely a function of the jet length. However, in valveless mode, the operating frequency is also a function of inlet length, but does not act as a ¼ wave tube. Rather, the frequency scales
with the inlet length raised to negative 0.22 power.

3. The operating frequency and peak pressure rise are a function of $\dot{m}_f$. At low $\dot{m}_f$, both frequency and pressure are low and increase with increasing $\dot{m}_f$. With the forward-facing inlet, the frequency and pressure both have a maximum, whereas with the rearward-facing inlet, the frequency continues to increase until the maximum $\dot{m}_f$ is reached. The pressure reaches a maximum at lower $\dot{m}_f$, but does not decrease as $\dot{m}_f$ continues to increase.

4. With forward-facing inlets, the net thrust is very low as expected. With rearward-facing inlets, the net thrust improves to approximately 1 N, resulting in a TSFC of 0.02 kg/N-hr.
Figure 3-1 8 cm pulsejets (dimensions in cm) (a) sketch for forward-facing inlet (b) photograph of rearward-facing inlet

Figure 3-2 The schematic for the experimental apparatus with rearward-facing inlet

Figure 3-3 The computational domain for the 8cm pulsejet, inlet length = 1.9 cm
Figure 3-4 Pressure vs. time for rearward-facing inlet configuration, total jet length = 8 cm (a) inlet length = 0.64 cm (b) inlet length = 1.9 cm
Figure 3-5 Operating frequency and peak pressure vs. inlet length

Figure 3-6 Pressure vs. time at various fuel flow rates, convention configuration
Figure 3-7 Frequency and peak pressure rise vs. fuel mass flow rate, forward-facing configuration

Figure 3-8 Frequency and peak pressure rise vs. fuel flow rate, rearward configuration
Figure 3-9 Forward-facing configuration thrust overlaying combustion chamber pressure, higher temporal resolution, $\dot{m}_r = 9 \text{ mg/s}$

Figure 3-10 Rearward configuration thrust overlaying combustion chamber pressure, higher temporal resolution, $\dot{m}_r = 8 \text{ mg/s}$
4 Combined Numerical and Experimental Investigation of a Hobby-Scale Pulsejet

4.1 Introduction

The pulsejet is perhaps one of the simplest propulsion devices, with passively moving reed valves being the only moving parts. The pulsejet has been described as a 1/4 wave tube, and clearly acoustics play an important role in its operation. The pulsejet is based on the Humphrey thermodynamic cycle, where isochoric heat addition (combustion) follows an isentropic compression and isobaric heat rejection follows an isentropic expansion. However, since the wave compression is weak, the thermodynamic efficiency is low, especially compared with the Brayton cycle where mechanical compression offers very high thermodynamic efficiency. In order to optimize and determine the scaleability of these propulsion devices, a better understanding of the interaction between the acoustics, fluid mechanics, and chemical kinetics is needed.

The concept of a pulsejet can be tracked back to the beginning of the 20th century. Two French engineers, Esnault and Peltrie, patented a design of an engine that drove a turbine wheel (Foa, 1960). The Esnault-Peltrie design was based on the principle of two opposing pulsating combustion columns fitted in a single straight tube. In the 1930’s, the German engineer Paul Schmidt designed the first working pulsejet, which was called the Schmidt tube (Reynst, 1961; Tsien, 1946). The first practical application of the pulsejet was the German Vergeltungswaffe-I (V-1) weapon (also known as the “buzz bomb” due to the low frequency acoustic emission) in World War II. It was a
pilotless flying bomb, which can be viewed as a prototype of a modern cruise missile.

Reynst (1961), best known for his ‘combustion pot’ discovery, believed that pulsejet engines operate on an acoustic resonating principle analogous to that of a 1/4 wave organ pipe. Reynst related the pressures and velocities in a characteristic Schmidt tube cycle to standing wave theory for small amplitude oscillations (i.e. by using linear acoustics). In a collection of works edited by Weinberg, Zinn (1986) gives a very thorough development of pressure oscillations in a closed tube driven by linear heat addition (i.e. amplitudes of oscillation and heat addition are small). Zinn suggests that the Esnault-Peltrie analysis can be easily adjusted for the 1/4 wave structure of a pulsejet simply by substituting the fundamental mode approximation for that of a tube open at one end and closed at the other. In theory, such a solution would determine the characteristics of the oscillations inside the engine and the range of operating conditions for which pulsating operation is possible.

Towards the later part of the second half of the century, interest in pulsejet applications quietly subsided. The continuing improvement of the turbojet (Brayton cycle) engine clearly gave it advantages as a propulsion system for atmospheric flight (higher thermodynamic efficiency, supersonic flight speeds, throttleability, etc.) over unsteady combustion technology (Shepherd, 1972). Most of these research efforts prior to the turbojet’s insurgence were pushed to the side and slowly forgotten amid the progress of technology. Pulsejets continued to be pursued by hobbyists for RC aircraft and boat propulsion. A very comprehensive review of hobby scale pulsejets is given by Boradin (1958); unfortunately, it has not been translated from Russian into English.
The pulsejet is an unsteady propulsion device that generates intermittent thrust. However, since the wave compression is weak, the thermodynamic efficiency is low, especially compared with the Brayton cycle where mechanical compression offers very high thermodynamic efficiency. This lack of thermodynamic efficiency is somewhat offset by the fundamental simplicity of the pulsejet. Although various designs were proposed after the first Schmidt tube, the basic design remains the same, and is shown in Figure 4-1. The reactants enter the tube when the pressure in the combustion chamber is lower than ambient pressure. Residual hot gases and heat transfer from the hot walls raise the reactant temperature above the auto-ignition temperature, initiating ignition and combustion of the reactants. The ensuing heat release increases the pressure, and these hot gases then expand down the exhaust duct and exit at high velocity, generating thrust. The hot gases at the exit have expanded to nearly atmospheric pressure and their momentum causes an expansion wave to propagate back up the exhaust duct towards the combustion chamber. When the expansion wave hits the reed valves, the sub-atmospheric pressure causes the valves to open, and fresh reactants are pulled into the combustion chamber, equalizing the pressure and closing the reed valves. The cycle then repeats itself.

In the 1/4 wave tube analysis (open at one end and closed at the other), the introduction of mass while the valves are open is neglected. In fact, when the valves are open, the resonant frequency corresponds to a 1/2 wave tube (open at both ends). Clearly, the 1/4 tube analysis cannot capture this. The thermodynamic cycle is also more complex than the Humphrey cycle because the combustion occurs neither isochorically
nor isobarrically, but somewhere in between, with the pressure rise in the combustion chamber being a competition between heat release rate (dictated by the chemical kinetics) and pressure release through expansion of products down the exhaust duct. Therefore, a more sophisticated computational model, validated by experimental measurements, is necessary to capture all the relevant physics.

The major advantage of a pulsejet is its simplicity. No mechanical compressor is needed to produce a pressure rise in the combustion chamber. However, early research has shown that pulsejets have low overall efficiency, which caused the termination of this line of research until recently, when it was found that thermodynamic efficiency of conventional engines (such as gas turbines) decreases non-linearly with decreasing the characteristic engine scale. Pulsejets are especially attractive as candidates for miniaturization due to their simple design.

The pulsejet investigated in this research is an off-the-shelf BMS pulsejet used by hobbyist for RC aircraft and boat propulsion. As shown in Figure 4-1, the BMS pulsejet consists of three sections: the valve head, the combustion chamber, and the exhaust duct. It has the total length of 50 cm (in this paper, the total length is defined as the length from the combustion chamber to the exit of the exhaust tube). Air and fuel are premixed in the valve head and enter the combustion chamber through reed valves. The reed valves are open when the pressure in the combustion chamber is lower than the ambient pressure and closed otherwise. A spark plug is used to ignite the air-fuel mixture. After several combustion events, the fuel and air mixture is ignited by the contact with the hot wall and the residual hot products in the pulsejet. Thus, the spark plug is only required to initiate
the combustion during the first few cycles.

The aim of the current research is to develop a detailed understanding of the chemical kinetic, fluid mechanic, and acoustic processes occurring within the pulsejet. An experimentally validated CFD model will allow the optimization of the pulsejet and help determine its suitability for miniaturization.

4.2 Hobby-Scale Pulsejet Operation Cycle

One of the most distinct characteristics of the pulsejet is the ominous sound (i.e., 120+ dB) caused by the combustion events that happen hundreds of times per second (for the hobby scale pulsejet). A wave diagram is shown in Figure 4-2 and illustrates the primary waves in the pulsejet. The ordinate spans from 0 to L, which corresponds to the inlet and the outlet of the jet, respectively. The abscissa can be treated as a non-dimensional time for one cycle. In each cycle, valves are first closed and a constant-volume (ideally) heat addition (combustion) generates compression waves simultaneously: a compression wave ‘a’ traveling downstream and a compression wave ‘b’ traveling upstream. The compression wave ‘a’ is reflected as a strong expansion wave ‘a1’ by the outlet of the jet. Since the opening of the reed valves is neglected, the left end of the pulsejet is modeled as an impermeable wall. The initial compression wave ‘b’ is reflected as a compression wave ‘b1’. When the wave ‘b1’ reaches the pulsejet exit, it is reflected as an expansion wave ‘b2’. The expansion wave a1 propagates upstream and when it enters the combustion chamber, the resulting sub-atmospheric pressure causes the reed valves to open and fresh reactants are pulled into the combustion
chamber. The expansion wave is reflected as an expansion wave at $x = 0$, and propagates down the exhaust tube, reflecting as a compression wave. When the compression wave enters the combustion chamber, the reactants are consumed, and the cycle repeats itself. As seen in this diagram, the primary acoustic wave propagates through the duct four times, hence the reason for analyzing this device as a 1/4 wave tube.

The actual events are obviously more complex than those shown in Figure 4-2. The opening of the valves and ensuing mass addition cannot be neglected. Due to geometric variations in the combustion chamber, there are a series of reflected waves traveling up and down the tube. The interactions between these waves make the analysis of the pulsejet operation extremely complex. Numerical simulation makes it possible to monitor different waves propagating in this system.

### 4.3 Experimental Setup

Fuel flow rates are measured with a rotameter for gaseous fuels and by mass balance for the liquid fuels. The data presented here is with liquid ethanol fuel. The liquid ethanol is pulled into the air flow in the venturi and vaporizes as it flows past the open reed valves and into the combustion chamber. Much difficulty was found in getting the pulsejet to run on gaseous propane due primarily to the destruction of the reed valves by the high temperature combustion process. The evaporation of the liquid ethanol aided in cooling the reed valves and this cooling effect was absent with the gaseous propane, resulting in excessive heating and valve failure. The jet is attached to a low friction bearing assembly for thrust measurements. To measure instantaneous thrust, a Kistler
piezoelectric force sensor combined with a Kistler charge amplifier was used. This load cell requires a preload, which was attained by securing the bearing shuttle with bungee cords to the test stand. To measure the instantaneous static pressure, Omega DPX101-250 high-speed pressure transducers were used in conjunction with an Agilent oscilloscope. Type-B thermocouples were used to measure average gas temperature inside the jet at various axial locations. In order to determine the location and characteristic times associated with the oxidation of the hydrocarbon fuel, a system of lenses, fiber optic cable, a filter, and a photo multiplier tube were used to detect the intermediate combustion radical, CH\(^{\ddagger}\). Instantaneous jet exit velocities were also measured using standard single component Laser Doppler Velocimetry (LDV), from which thrust could be calculated and compared with the measured thrust and used to validate the computational model.

Several jet configurations based on the BMS pulsejet were used in this research. The total length of the standard configuration is 50 cm. The exhaust tube is 3.2 cm in diameter but flare to 3.8 cm at the exit. There are ten 0.87 cm-diameter holes on the valve head through which the air/fuel mixture enters the tube. Three ports were welded on to the pulsejet along the jet axis for diagnostic measurements. The port locations can be seen in Figure 4-1, where Port 1, 2, and 3 are 2 cm, 15 cm, and 47 cm from the beginning of the combustion chamber, respectively. Temperature, pressure, and CH\(^{\ddagger}\) data were taken at each port (the latter two simultaneously). Additional tail pipe extensions were manufactured so that the jet could be lengthened in 7.5 cm increments to determine the relationship between the exhaust duct length and engine operation.
4.4 Numerical Model

The computational domain has exactly the same geometry and dimension as the BMS jet. For simplicity, the reed valves and the valve retainer were not modeled. The function of the reed valve was modeled by supplying an equation relating the inflow velocity \( V_{\text{inflow}} \) and the pressure difference across the valve. This equation, obtained from experimental measurements in the actual pulsejet venturi-reed valve assembly, is given below:

\[
V_{\text{inflow}} = \begin{cases} 
\frac{3(P_0 - P_1)}{1000} [\text{m/s}] & P_1 < P_0 \\
0 & P_1 > P_0
\end{cases}
\]

where \( P_1 \) is the pressure immediately after the reed valve and \( P_0 \) is the ambient pressure.

The inflow velocity has a 25 degree radially outward trajectory, similar to that observed in the experiments. The flow in the pulsejet is assumed to be axially symmetric; therefore, the computational domain is only 1/10 of the actual pulsejet, or 36 degrees in the \( \theta \) direction.

The current study models unsteady, three-dimensional, compressible, viscous flow with heat transfer and radiation. The CFX5.7 software package is utilized. The second order transient scheme and high-resolution advection scheme are used to capture the compression/expansion waves. The timestep is chosen such that the Courant number is unity and the solution has a convergence criterion of \( 10^{-4} \) in residual mean square value.

The computations are performed on the NC State IBM Blade center utilizing a
single 3.0GHz Intel Xeon processor. Typical computational time for one cycle of the pulsejet is 20 CPU hours. The turbulent flow is modeled using a k-ε model based on the Reynolds Averaged Navier-Stokes (RANS) equations. The viscous effect in the boundary layer region is modeled by the log-law, in which the empirical formulas are provided to connect the wall conditions to the dependent variables at the near-wall mesh node.

Governing equations for the fluid flow are given below. The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$  \hspace{1cm} (4-2)

the momentum equation based on the eddy viscosity assumption is given by

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = \nabla p' + \nabla \cdot [\mu_{\text{eff}} \mathbf{U} + (\nabla \mathbf{U}^T)]$$  \hspace{1cm} (4-3)

where \( \mu_{\text{eff}} \) is the total viscosity that accounts for turbulent viscosity, and \( p' \) is the modified pressure given by

$$p' = p + \frac{2}{3} \rho k$$  \hspace{1cm} (4-4)

The k-ε model is based on the eddy viscosity concept, which assumes:

$$\mu_{\text{eff}} = \mu + \mu_t$$  \hspace{1cm} (4-5)

where \( \mu_t \) is the turbulent viscosity:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$  \hspace{1cm} (4-6)

The k-ε model includes the following equations for the kinetic energy, \( k \), and the dissipation rate of turbulence, \( \varepsilon \):
\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon \tag{4-7}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho U \varepsilon) = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} (C_{e1} P_k - C_{e2} \rho \varepsilon) \tag{4-8}
\]

where \( C_{e1}, C_{e2}, \sigma_k \) and \( \sigma_\varepsilon \) are model constants (their values are given in Table 4-1) and \( P_k \) is the turbulence production due to the viscous force:

\[
P_k = \mu_1 \nabla U \cdot (\nabla U + \nabla U^T) - \frac{2}{3} \nabla \cdot U (3\mu_1 \nabla \cdot U + \rho k) \tag{4-9}
\]

The energy equation is:

\[
\frac{\partial (h + \frac{1}{2} U^2 + k)}{\partial t} - \frac{\partial P}{\partial t} + \nabla \cdot [\rho U (h + \frac{1}{2} U^2 + k)] = \nabla \cdot \left( \lambda \nabla T + \frac{\mu_t}{P_{r_t}} \nabla h \right) + S_E \tag{4-10}
\]

The model assumes complete vaporization and mixing producing homogeneous premixed reactants at an overall stoichiometric ratio of unity. The Eddy Dissipation Model (EDM) is used to simulate the unsteady combustion process (CFX-5 online help, 2004; Poinsot & Veynante, 2001; Pope, 2002). The only reaction products are CO₂ and H₂O. The EDM assumes that either reaction is fast compared to turbulent mixing (high Damköhler number), or the reaction rate is proportional to the timescale of turbulent mixing. The timescale of turbulent mixing, which depends on the eddy properties, is determined as the ratio of \( k \) and \( \varepsilon \).

The reaction rate is determined from the minimum of expression (4-11) and expression (4-12) below:
\[ R_k = A \frac{\varepsilon}{k} \min \left( \frac{[I]}{v^e_{KI}} \right) \sum [I] W_I \]  
\[ R_k = AB \frac{\varepsilon}{k} \left( \sum_P W_I v^e_{KI} \right) \]  

(4-11)  

(4-12)  

where \([I]\) is the molar concentration of the reactant I and \(P\) loops over all product components. \(A\) and \(B\) are model constants and their values are given in Table 4-1. The auto-ignition and flame quenching process are modeled with two parameters: chemical timescale and extinction temperature. In this case, chemical timescale is 0.0004 s and extinction temperature is 800 K. Auto-ignition happens when the chemical timescale is smaller than the local turbulence timescale and the local temperature is higher than the extinction temperature. The turbulence timescale is calculated from the flow field as \(k/\varepsilon\). Similarly, the flame is locally quenched whenever the temperature is less than the specified extinction temperature, or the chemical timescale is larger than the turbulence timescale. This extinction temperature was chosen based on experimental measurements of pressure and oscillation frequency.

**4.5 Results and Discussions**

Figure 4-3 shows an example of the simulation results for the BMS pulsejet. The pulsejet is static and the wall temperature is 300 K. The pressure outside the pulsejet is atmospheric. The stoichiometric fuel/air mixture enters the combustion chamber with the velocity described by Eq. (4-1). The pressure, temperature, axial velocity \(u\), and fuel mass fraction on the cross-section of the pulsejet for one cycle are shown in Figure 4-3.
The general pulsejet cycle can be illustrated as the following. The combustion event occurs when the combustion chamber pressure is above atmospheric and the temperature of the fuel/air mixture increases, due to mixing with residual products, to the auto-ignition temperature. A compression wave is generated and increases temperature and pressure in the combustion chamber, driving the flow toward the exit at gradually increasing velocity. When the compression wave reaches the pulsejet exit, expansion waves are generated due to overexpansion and travel back to the combustion chamber. Flow velocity reaches its positive maximum near the exit. The expansion wave decreases the pressure in the tube and the combustion chamber to subatmosphere and backflow occurs at the exit. When the combustion chamber pressure is below atmospheric, reed valves open up and let the next charge of fuel/air mixture into the chamber. This mass addition, along with the backflow, increases the combustion chamber pressure. When the pressure in the combustion chamber approaches the atmosphere pressure, the next cycle begins.

The first 5 steps in Figure 4-3 can be treated as the filling process while the second 5 steps are the burning process. Reaction occurs at the beginning of the burning process. Most of the combustion chamber is filled with the reactants during the filling cycle. This confirms that the drop of temperature at port 1 is caused by cold reactants. The fuel/air mixture is injected towards the wall and generates a strong vortex behind the valve. This enhances turbulence in this region and increases the reaction rate as well since the reaction rate, according to EDM, is proportional to the turbulence intensity. It is found that during the fuel burning process, there is a small amount of fuel along the wall.
in the transition region that does not burn. This is not expected because experiments indicate that the wall temperature in this region is always high enough to ignite the fuel. A possible reason is that in the wall region, the turbulence timescale is very small due to the small turbulence kinetic energy. If this small turbulence timescale is smaller than the chemical timescale, the flame extinction in that region is enabled in the simulation model. Further work is needed to investigate the influence of the chemical timescale.

Figure 4-4 a-c shows the experimental and computational pressure versus time at three ports. The measured frequency is 232 Hz, with a fluctuation of approximately 10 Hz, while the computed frequency is 242 Hz; this is a very good agreement. To compare structure, the time scales have been stretched so that the experimental and computational oscillations coincide. The peak pressure in the combustion chamber (port 1) is calculated to be 0.17 MPa, in very good agreement with the experimental measurements. The model is also able to replicate the small pressure blip on the rising part of the oscillation, most likely due to acoustic wave reflections. The model does not do as well in predicting the negative pressures measured in the combustion chamber, where the measurements are considerably more negative. Recall that the valves are not being modeled, so it is not surprising that the model does a relatively poor job at predicting the minimum pressures. The total fuel flow rate is the same in both the computations and the experiments however. In Figure 4-4c, a complex exhausting process is observed both computationally and experimentally, with multiple reflections occurring at the jet exit. The code does a remarkably good job at predicting these multiple reflections.

By drawing a line at the ambient pressure (0.1 MPa), it is evident that each cycle
consists of a high-pressure portion and a low-pressure (sub-atmospheric) portion. The positive and negative peaks are approximately equal in magnitude; however, the upper portion is always slightly larger. This happens because the flow is nearly fully expanded at the exit and reflected expansion waves have an approximately same strength as the compression waves (See Figure 4-2, waves ‘a’ and ‘a1’). The small difference between the peaks is primarily caused by the inflow of reactants, valve losses, and viscous losses. The strength and the number of reflected expansion waves are important to the pulsejet operation because they create the necessary sub-atmospheric condition in the combustion chamber. This phase of the engine’s cycle must be sufficiently long in duration to permit sufficient reactants to enter the combustion chamber to initiate the next cycle.

During a cycle of operation, the pulsejet is constantly changing its acoustic characteristics. For example, while the valves are open, the acoustic wave perceives the tube as a 1/2-wave tube with pressure release surfaces seen at either end. Yet, while the valves are closed, the jet behaves as a 1/4-wave tube where a solid wall boundary replaces the pressure release surface at the front end. However, due to the change in the cross section area, the jet behaves more like a 1/6-wave tube, which is indicated by the frequency data. This is so because the area change results in complex wave interactions in the pulsejet. The operation frequency is also affected by the temperature inside the pulsejet, which determines the local speed of sound.

In order to see when this pressure rise is occurring as compared to the combustion, CH* at port 1 was measured, and the result is shown in Figure 4-5. CH* is a short-lived intermediate combustion radical appearing only in an active reaction zone.
The measurements were made by setting up lenses attached to a fiber-optic cable to capture the light emitted from port 1. The emission was transmitted through a 430 nm (the wavelength emitted by CH\(^*\)) filter and measured by a photomultiplier tube (PMT) attached to an oscilloscope. It was found that the pressure peaks resulting from reflected waves coincide with the peak combustion pressure events in order to attain resonance. These results suggest that chemical times (responsible for controlling fluid dynamic times) must be similar to acoustic times to assure dependency. From Figure 4-5 it is evident that combustion occurs mostly during the super-atmospheric portion of the cycle. The sub-atmospheric portion, when fresh reactants are introduced, shows no CH\(^*\), and therefore no combustion. A finite amount of time is required for the residual hot products to mix with the fresh reactants and raise their temperature to the auto-ignition temperature. This information is used in the EDM simulations to model the flame extinction.

The duty cycle of the reed valves (i.e., the duration they spend open during each cycle) was also measured, and these results are presented in Figure 4-6. A He-Ne laser and high-speed camera were utilized to make these measurements. The laser was used to ‘paint’ a spot on the valve to make use of the camera’s limited light sensitivity at high speed. The painted spot was observed to move when the valves were open due to their deflection. The camera acquired images at 2 kHz while the jet operated at 230 Hz, so there were a little over 9 frames acquired per cycle. After looking over many cycles, the results were then averaged and it was concluded that the valves remained open for approximately 30% of the cycle duration. This information was used to validate the inlet
boundary conditions in the computation model, where the valve operation was simplified. The duration for the premixed reactants to enter the combustion chamber should be approximately 30% of the cycle duration.

The pulsejet thrust was measured experimentally, both instantaneous and mean, and computed. Figure 4-7 shows the measured instantaneous thrust and the simultaneously measured pressure at port 2. The mean thrust was measured to be 25 N by compressing a spring with known spring constant. As observed in Figure 4-7, the thrust oscillates at the same frequency as the pressure, but is 180 degree out of phase as expected because the pulsejet trades the high static pressure for the high exhaust velocity. The negative thrust is caused by the backflow. In order to increase thrust, the backflow can be reduced; the frequency and the mixing rate can be increased. Of these options, the reduction of backflow is most challenging because the backflow is related to many factors such as the pressure rise and pulsejet length. The simulated thrust is plotted with experimental result for thrust and shown in Figure 4-8. The frequency is the same, as expected, and the model is predicting the complex double peak structure observed in the measurements. However, the magnitude is not well predicted. One possible reason for this is the wall temperature for the simulation may lower than the experiments, which would result in a loss of enthalpy.

The exit velocity was also measured using a single component LDV setup operating in a forward scattering mode. A curve fit of the experimental data clearly shows a sinusoidal behavior, with a frequency of 235 Hz, and is shown in Figure 4-9. There is a strong negative component of velocity during a part of the cycle. This
confirms the negative thrust predicted and measured in this pulsejet. To our knowledge, this is the first time a negative velocity in the pulsejet has been reported.

Figure 4-10 shows the temperature data at the three ports. Due to the finite size of the thermocouple bead, instantaneous temperature measurements were not possible and only cycle-averaged temperatures are shown. Computational results show that port 1 has the highest peak temperature while port 2 has the highest mean temperature. The majority of the combustion process is occurring near port 1, and thus the peak temperature occurs at this location. The mean temperature (both measured and calculated) is lower at port 1 due to the cold reactants being introduced during each cycle. As seen in the simulation results at port 2, the cold reactants do not penetrate this far upstream before reacting, thus the mean temperature is much closer to the peak temperature at this location. The peak temperature is lower at port 2 than port 1 due to heat losses to the walls (which is included in the model). Port 3 has the lowest temperature due to both expansion of the hot gases and heat loss to the wall. It is also clear from the temperature simulations that the ambient air is entrained into the exhaust duct during a portion of the cycle. The cycle-averaged computational temperatures are compared with the measured mean temperatures. At port 1, the calculated temperature of 1900 K is 50 K higher than the measured mean temperature of 1850 K, while at port 2, the calculations overpredict the temperature by 130 K, and underpredict the temperature at port 3 by 60 K. Recall that the thermocouple measurements are not radiation corrected, having the greatest effect on port 2 which has the highest mean temperature. The computational model assumes that the environment is always at 300 K, so the
ambient air that is entrained during the negative exit velocity portion of the cycle artificially depresses the mean cycle-average temperature because the hot gas from the jet increases the outside air temperature, and this is neglected in the model.

The peak temperatures in ports 1 and 2 are coincident in time, indicating multiple ignition sites and nearly homogeneous burning of reactants in the combustion chamber. The peak temperature at port 3 is delayed in time relative to ports 1 & 2 due to the finite propagation time of the hot products. More details of each temperature profile are given in Figure 4-11-Figure 4-13 below.

Figure 4-11 shows an expanded view of the temperature profile at port 1, just behind one of the valves. Features such as the introduction of fresh reactants, their warming up to the auto-ignition temperature, their reaction and resulting heat release, and then their cooling due to expansion converting this thermal enthalpy into kinetic energy (and thus thrust) are all readily apparent.

In Figure 4-12, it is shown that the temperature does not change a great deal during the cycle. The hot gases provide the thermal energy necessary to ignite the subsequent reactant charge. The temperature difference will be due to a combination of kinetic energy generation and heat losses through the walls, which is being modeled.

Figure 4-13 shows the temperature time history near the exit plane. The pressure is very dynamic at the exit due to interactions of the acoustic waves and material waves with the ambient surroundings. The material wave (fluid mechanic wave) makes one round trip during a complete cycle. One trip is for the compression waves traveling from combustion chamber to the exit and the other is for expansion waves traveling back to the
combustion chamber. The acoustic wave makes two round trips during the same cycle. The presence of the acoustic wave is clearly seen in the temperature profile, showing up as local maxima. The model is also accurately predicting the negative velocity during the refraction wave portion of the cycle, as evidenced by the very low temperatures in the exit duct. This corresponds to ambient air being pulled into the exit duct; the ambient air is always at 300 K. The expansion of the hot gases leaving the exhaust duct is not modeled. It is evident that there will be some expansion waves at the exit because the gases are under-expanded. Thus, the fluid which is pulled into the exhaust duct will contain some warm products; however, it is not believed to have a major effect on pulsejet operation.

As stated above, in order to obtain higher thrust, it is desirable to have high operation frequency and mixture ratio. For a fixed size of the combustion chamber and fixed mixture ratio, changing the operation frequency can be accomplished by varying the jet length. The relation between the jet length and the operation frequency, obtained both experimentally and computationally, with good agreement between the two, is shown in Figure 4-14. The solid line in Figure 4-14 represents a 1/L curve fit.

### 4.6 Conclusions

A better understanding of the pulsejet as a propulsion device has been achieved through a coupled experimental/computational study of a hobby scale pulsejet. This 50 cm valved pulsejet produced an average thrust of 25 N and operating frequency of 240 Hz when running on ethanol. The measured exit velocity, via LDV, behaves like a 235
Hz sinusoidal wave, with a significant negative velocity component. A He-Ne laser and high-speed camera were utilized to examine the duty cycle of the reed valves, and used as an input for the computations, and reveals that the valves remained open for approximately 30% of the cycle duration. CH$^*$ was measured to determine the location and temporal extent and characteristics of the combustion event. Combined with simultaneous combustion chamber pressure measurements, it is evident that combustion happens in during the super-atmosphere portion of the cycle. The experimentally validated simulation model shows that the reflected expansion waves create the necessary sub-atmospheric condition in the combustion chamber, the strength and the number of these waves are important to the pulsejet operation. The duration of the low-pressure phase of the engine’s cycle must be sufficiently long to permit sufficient reactants to enter the combustion chamber to initiate the next cycle. The analysis of peak temperatures in different axial positions indicates multiple ignition sites and nearly homogeneous burning of reactants in the combustion chamber. The simulation also shows the location and size of the vortex in the combustion chamber generated by the injection of the fuel/air mixture, which increases the reaction rate since the reaction rate is proportional to the turbulence intensity. The acoustic model for the 50 cm valved pulsejet is a function of many factors such as valve duty cycle, temperature, combustion chamber volume, and total length. Acoustically, the pulsejet can be modeled as a 1/6-wave tube, and this new model is verified by both the experimental and computational results.
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Figure 4-1 BMS pulsejet geometry and dimensions (a) the pulsejet sketch (b) the valve head.

Figure 4-2 Wave diagram for valved pulsejet operation.
Figure 4-3 Simulation results of the pulsejet cycle: a) Pressure, b) Temperature, c) Velocity, and d) Fuel mass fraction.
Figure 4-4 Instantaneous pressure, both measured and calculated at (a) port 1 (b) port 2 (c) port 3.

Figure 4-5 CH* chemiluminescence measurements and experimental combustion chamber pressure.
Figure 4-6 The open/close duty cycle for the reed valves.

Figure 4-7 Instantaneous thrust and port 2 pressure measurements.
Figure 4-8 Instantaneous thrust comparison between measurement and calculation.

Figure 4-9 Measured exit velocity via LDV with 235 Hz sine wave curve fit.
Figure 4-10 Calculated temperature at three axial locations, with comparison to measured (mean) temperatures, T1-T3 corresponding to axial location 1-3. Cycle-averaged calculated temperature shown at bottom of figure.
Figure 4-11 Details of calculated temperature at port 1 (just behind 12 valves).

Figure 4-12 Details of calculated temperature at port 2 (end of combustion section).
Figure 4-13 Details of calculated temperature at port 3 (near the exit plane).

Figure 4-14 Effect of pulsejet length on frequency, both experimental and calculated, with inverse length curve fit.
5 The Effect of Starting Vortex Ring on Pulsejet Thrust

5.1 Introduction of Vortex Ring and its Relation to Pulsejet

Studies of vortex ring formation date back to 1900’s and this phenomenon has been extensively investigated theoretically, numerically, and experimentally (Maxworthy, 1974; Shariff & Leonard, 1992; James & Madnia, 1996; Nitsche, 1996; Rosenfeld et al., 1998). Most of the work on vortex rings have used piston-cylinder devices with various length-to-diameter, $L/D$, aspect ratios to form a vortex ring at the end of the orifice. Previous investigations of vortex rings typically considered low Reynolds number flows and constant density fluids. Although previous research provided considerable insight into the vortex ring formation and evolution, there are a number of unique issues associated with vortex ring formation in unsteady propulsion devices.

An early study of vortex rings generated by an unsteady jet was performed by Gawthrop et al. (1931) who established the existence of the vortex ring at the orifice of a shock tube. Elder and Haas (1952) conducted an experimental study of the formation and acceleration of the vortex ring at the open end of a cylinder shock tube. Siekmann (1963) presented a theoretical analysis of the unsteady periodically working jet propeller, whose design was based on the propelling mechanism of certain aquatic animals such as squid. However, none of these vortex investigations were directly applicable to a pulsejet. Gharib et al. (1998)) were the first to relate starting vortex rings to a propulsion device. Their results show that the Formation number, defined as the limiting value of $L/D$ (vortex rings generated above this limiting value of $L/D$ do not absorb all of the
discharged fluid’s mass or vorticity), is between 3.6 and 4.5, suggesting that a universal value for the Formation number may exist. Paxson and Wernet (2004) investigated the unsteady thrust augmentation using a speaker-driven jet. Their results show that the Formation number is a relevant, although not sufficient, parameter for evaluating the performance of an unsteady ejector. More recently, Krueger and Gharib (2003) studied the significance of vortex ring formation to the impulse and thrust of a starting jet. Using two different piston velocity profiles they showed that the starting vortex ring formation and pinch off (defined as the state at which vortex ceases to accept additional vorticity from the shear layer) is critical to the thrust and impulse produced by starting jets. It was also found that the nozzle exit over-pressure contributed as much as 42% of the total impulse for cases involving isolated vortex rings. However, as they stated, the hypothesis that the vortex ring pinch off is significant for propulsion relies on the relative significance of the leading vortex ring to the trailing jet for generating thrust. Although no attempt was made to design a real pulsed-jet device to examine their conclusions, Krueger and Gharib (2003) made some suggestions for such unsteady propulsion devices such as synthetic jets.

Since the pulsejet is an unsteady device, the exhaust flow is dominated by the starting vortex. This paper investigates starting vortex rings generated by the exhaust flow from a static hobby-scale pulsejet. In our previous work (Geng et al., 2007) we found that the flare at the end of the pulsejet plays a significant role in the pulsejet operation due to the fact that adding a flare lowers the combustion chamber pressure during the filling process, thus increasing the fuel/air flow rate. We believe that the
primary difference between a flared and an unflared pulsejet is the vortex ring generated in both cases, which affects the combustion chamber pressure and hence the fuel flow rate. In addition, the optimal $AR$ at which the pulsejet generates maximum thrust for given operating conditions is obtained. Finally, the significance of the pinch off of the starting vortex ring to the pulsejet thrust is studied.

### 5.2 Numerical Model

The pulsejet modeled in this research is an off-the-shelf Bailey Machining Service (BMS) pulsejet used by hobbyists for RC aircraft and boat propulsion (Geng et al., 2007). As shown in Figure 5-1 and Figure 5-2, the BMS pulsejet has three parts: combustion chamber, transition section, and constant-area tail pipe. Different flare designs were investigated and the flares were attached to the end of the tail pipe. Unlike most other investigations which use $L/D$ as the key parameter, a new dimensionless parameter, the ratio of the exit plane area of the flare and the cross-sectional area of the pulsejet tailpipe, $AR$, is used in this analysis. The computational domain includes the pulsejet and a large region outside of the pulsejet to model the external flow. The current study models unsteady, three-dimensional, compressible, viscous flow with heat transfer and radiation utilizing CFX5.7 software package (Geng et al., 2007). A second order transient scheme along with a high-resolution advection scheme are used to capture the compression/expansion waves. The timestep is chosen such that the Courant number is unity and the solution has a convergence criterion of $10^{-4}$ in the residual mean square value.
The computations are performed on the NC State IBM Blade center utilizing a single 3.0G Hz Intel Xeon processor. Typical computational time for one cycle of the pulsejet is 20 CPU hours. The turbulent flow and reaction rate are modeled with the $k$-$\varepsilon$ model and the Eddy Dissipation Model (EDM), respectively. The viscous effect in the boundary layer region is modeled by the log-law, in which the empirical formulas are provided to connect wall conditions to dependent variables at near-wall mesh nodes. The validations of the code can be found in our previous work (Geng et al., 2007).

Governing equations for the fluid flow are given below. The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \quad (5-1)$$

the momentum equation based on the eddy viscosity assumption is given by

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = \nabla p' + \nabla \cdot [\mu_{\text{eff}} (\nabla \mathbf{U} + (\nabla \mathbf{U})^\top)] \quad (5-2)$$

where $\mu_{\text{eff}}$ is the total viscosity that accounts for turbulent viscosity, and $p'$ is the modified pressure given by

$$p' = p + \frac{2}{3} \rho k \quad (5-3)$$

The $k$-$\varepsilon$ model is based on the eddy viscosity concept, which assumes:

$$\mu_{\text{eff}} = \mu + \mu_t \quad (5-4)$$

where $\mu_t$ is the turbulent viscosity, defined as:
\[ \mu_t = C_\mu \frac{k^2}{\varepsilon} \] (5-5)

The \( k-\varepsilon \) model includes the following equations for the kinetic energy, \( k \), and the dissipation rate of turbulence, \( \varepsilon \):

\[ \frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho U k) = \nabla \cdot \left( \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \nabla k \right) + P_k - \rho \varepsilon \] (5-6)

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho U \varepsilon) = \nabla \cdot \left[ \left[ \mu + \frac{\mu_t}{\sigma_\varepsilon} \right] \nabla \varepsilon \right] + \frac{\varepsilon}{\kappa} (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon) \] (5-7)

where \( C_{\varepsilon 1}, C_{\varepsilon 2}, \sigma_k, \) and \( \sigma_\varepsilon \) are model constants (their values are summarized in Table 5-1) and \( P_k \) is the turbulence production due to the viscous force:

\[ P_k = \mu_t \nabla U \cdot (\nabla U + \nabla U^T) - \frac{2}{3} \nabla \cdot U (3 \mu_t \nabla \cdot U + \rho k) \] (5-8)

The energy equation is:

\[ \frac{\partial \rho (h + \frac{1}{2} U^2 + k)}{\partial t} = \frac{\partial p}{\partial t} + \nabla \cdot [\rho U (h + \frac{1}{2} U^2 + k)] = \nabla \cdot \left( \lambda \nabla T + \frac{\mu_t}{Pr} \nabla h \right) + S_e \] (5-9)

### 5.3 Results and Discussions

#### 5.3.1 The Effect of Flare on the Pulsejet Starting Process

The results for \( AR=1 \) (i.e. without flare) and \( AR=1.4 \) (typical hobby scale geometry) are compared to examine the effect of the flare. Two simulations are...
performed using the same initial condition (Geng et al., 2007) but different flare designs. After a few cycles, quasi-steady-state is achieved and the geometry with $AR=1.4$ produced higher combustion chamber pressure and generates more thrust. The quasi-steady-state pressure and velocity profiles for $AR=1.4$ and $AR=1$ cases are shown in Figure 5-3(a-b). This figure shows that a flare can help the pulsejet to start by increasing the chamber pressure as indicated by experimental data (Geng et al., 2007). The experimental data also shown that flared pulsejet has lower minimum exit pressure and thus lower minimum chamber pressure, which increases the reactant mass flow rate across the valves in the inlet. It is this increased mass flow rate that causes higher maximum chamber pressure. However, no experimental data directly relates flare to minimum exit pressure. Figure 5-4 shows the computational results for pressure at various locations downstream of the pulsejet exit for different flare geometries at the temporal location of maximum exit velocity within the cycle. The pressures plotted are at the cross-section plane of the vortex ring. As shown in this figure, the pressure is much lower for the flared pulsejets, and the largest $AR$ produces the lowest minimum pressure.

Figure 5-5 shows the effect of the flare geometry on the minimum exit pressure and the vortex ring circulation at the time of minimum exit pressure. The vortex ring circulation is defined as:

$$\Gamma = \int_{A} \omega dA$$  \hspace{1cm} (5-10)

where $\omega$ is the ring vorticity and $A$ the vortex ring area. The minimum exit pressure
throughout a cycle decreases sharply as $AR$ increases, reaching a minimum before leveling off at large $AR$. The total circulation behaves oppositely, increasing rapidly with $AR$ and then falling off with increasing $AR$. This is explained by the fact that the vortex ring of the flared pulsejet has larger circulation and diameter, which pulls more fluid out of the jet exit, thus decreasing the exit plane pressure.

Figure 5-6(a-b) show uniformly scaled velocity vectors superimposed with vorticity contours. It is evident from these plots that the distance from the vortex core to the centerline for the flared pulsejet is always larger than that for the unflared pulsejet. In other words, the diameter of the vortex ring for the flared pulsejet is larger. The initial vorticity for the flared pulsejet is also larger due to two facts: 1) the flare helps flow rotate around the edge of the flare, which increases the initial vorticity, and 2) as the cross-section area of the flare increases, the flow velocity decreases in the flare region. Compared with a constant-area exhaust pipe (Figure 5-6 (a)), the flare increases the velocity gradient and moves the boundary layer separation point upstream from the jet exit. As shown in Figure 5-6, the maximum vorticity occurs at the edge of the jet exit.

5.3.2 Optimal $AR$ for the Maximum Thrust

Simulations were run with the following $AR$ values: 1, 1.4, 2, 3.1, 4.3, and 8.0. The flare geometries are designed to have a curve to avoid the generation of a secondary vortex inside the flare. Figure 5-7 shows that thrust increases dramatically with a flared exit, reaching a maximum at $AR=2$ before slowly trailing off. Although thrust is of primary importance, it is also necessary to minimize thrust specific fuel consumption
(TSFC). As seen in this figure, TSFC reaches a minimum value of 2.86 also at $AR$ value of 2. Pulsejets with the same geometry are investigated with 60% of the original fuel flow rate for four different $AR$ values as well, with results listed in Table 5-2. The maximum thrust at this reduced fuel flow rate also occurs at $AR=2$. Table 5-2 lists total thrust and negative thrust caused by the adverse pressure in the flare region. $P_1$ refers to the combustion chamber pressure. Thrust is calculated through pressure forces acting on the pulsejet walls:

$$F = \int_{A} (P - P_0) dA$$  \hspace{1cm} (5-11)

where $P_0$ is the ambient pressure. Table 5-2 shows that with the increase of $AR$, the peak pressure in the combustion chamber increases, resulting in an increase of the thrust. However, the area change also causes a large adverse pressure region in the larger $AR$ cases. Thus at $AR$ greater than 2, the net thrust decreases due to this larger negative contribution.

5.3.3 The Significance of the Starting Vortex Ring Circulation to Pulsejet Thrust

The vortex ring circulation vs. time is plotted in Figure 5-7 for seven different $AR$ values. $T=0$ corresponds to the formation of the vortex ring and the maximum circulation point corresponds to the pinch off. $AR$ values larger than two may not be practical, but were simulated to understand the relation between circulation, pinch off time, and net thrust. As shown in this figure, for various flare geometries the vortex rings undergo a similar evolution process, the circulation of the vortex ring increases after its formation.
and reaches maximum point where vortex ring is pinched off from the trailing jet. The flare with $AR=1.4$ has the maximum circulation value while the flare with $AR=2.0$ has the maximum pinch off time (defined as the time interval between the formation of vortex ring and the moment of pinch off). For larger $AR$ flares, although the circulations for the vortex rings are high, the pinch off time is generally much shorter than those in the smaller $AR$ flares. Figure 5-8 shows the pinch off time for each flare, suggesting that as $AR$ increases from 1 to 36, the pinch off time first increases, reaches a maximum value at $AR$ approximately equal to 2, and then decreases. This result suggests that to maximize net thrust, the pulsejet exit geometry must produce a vortex ring with a long pinch off time. Formation number, $F$, a non-dimensional time studied by Ghraib (1998), is defined as the limiting value of $L/D$ for which a vortex ring generated with values above this limiting value do not absorb all of the discharged fluid’s mass or vorticity. The Formation number $F$ is defined as:

$$F = (\frac{L}{D})_{lim}$$

(5-12)

where

$$L = \int_0^{t_{pinch}} u_{exit} \, dt$$

(5-13)

$t_{pinch}$ is the time between vortex ring formation and pinch off, and $D$ is the diameter of the pulsejet exhaust pipe. In other words, the maximum circulation is reached at this universal time scale. To compare the Formation number in an unsteady pulsejet and the steady piston-cylinder device, the Formation number of the pulsejet is calculated for
various $AR$ values and plotted in Figure 5-10. As shown in Figure 5-10, thrust performance of the pulsejet is a strong function of the Formation number. Thrust increases as $F$ increases and reaches its maximum value at $F=3.9$ and decreases as $F$ further increases. This relationship between Formation number and thrust performance is also shown in Paxon and Wernet’s study (2004) where thrust augmentation first increases as $F$ increases and reaches maximum value when $F$ is around 8 and decreases as $F$ further increases. Both cases indicate that the Formation number is a relevant design parameter for optimization of the unsteady propulsion device. It is interesting to note that the maximum thrust flare has a Formation number of 3.9, which falls in the range of 3.6 to 4.5 as reported by Ghraib et al. (1998).

### 5.4 Conclusions

This paper investigated the effect of a flared geometry on the operation of a 50 cm hobby-scale pulsejet. We defined a new dimensionless parameter $AR$ to characterize this effect. The vortex ring generated at the exit of the pulsejet was studied. The following conclusions can be drawn:

1. The pulsejet with a flare is easier to start because the flare creates a larger vortex ring diameter, larger initial circulation, and longer pinch off time. This results in lower minimum pressure at the exit and hence in the combustion chamber, which increases the reactant flow rate into the pulsejet to initiate the next cycle.

2. The pulsejet produces maximum thrust when the vortex ring generated by its
exhaust flow has the longest pinch off time. For pulsejets operating at two different levels of combustion peak pressures, the maximum thrust occurs at $AR$ value of 2. The curvature of the flare helps increase the initial circulation; however, it also produces an adverse pressure region in the flare and decreases the total thrust, especially in cases with large $AR$ values.

(3) The Formation number for various $AR$ values shows that thrust is a strong function of this parameter and the maximum thrust case occurs for the geometry with a Formation number of 3.9, which falls in the range calculated by Ghraib et al (1998).
Table 5-1 Constants used in CFX computational code

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Table 5-2 Pulsejet thrust at 60% of the original fuel flow rate

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<td></td>
<td>Low</td>
<td>0.86</td>
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<tr>
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<td>0</td>
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<td>-1.88</td>
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<tr>
<td>Total Thrust (lbs)</td>
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<td>2.25</td>
<td>3.0</td>
<td>2.23</td>
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Figure 5-1 Computational domain for the 50 cm hobby-scale pulsejet

Figure 5-2 The dimensions of the hobby-scale pulsejet (mm)
Figure 5-3 Velocity and pressure profiles of the pulsejet with $AR=1.4$ (a) and $AR=1$ (b)
Figure 5-4 Pressure in the vortex ring core for various flare geometries as a function of downstream distance (x=0 corresponds to exit plane)
Figure 5-5 Pulsejet minimum exit pressure and circulation vs. AR
Figure 5-6 Velocity vectors and vorticity contours for AR=1 (a) and AR=1.4 (b) at pinch off
Figure 5-7 Thrust and TSFC vs. AR
Figure 5-8 Starting vortex ring circulation vs. time
Figure 5-9 The pinch off time vs. AR

Figure 5-10 Pulsejet thrust and Formation number
6 Summary and Future Work

6.1 Summary

This research studies various topics in the operation of pulsejet. Numerical simulations were conducted to explore the scalability of valveless pulsejets; study the operation cycles for various pulsejets; and provide a better understanding of the exhaust flow of these pulsejets. Main conclusions from these topics are:

(1) Simulations show previously unknown details of the operation processes for both the valved and valveless pulsejets. One of the main differences in the operation process between valved and valveless pulsejets is the air breathing mechanism. Although both mechanisms share the fact that air enters the combustion chamber when pressure in the combustion chamber is lower than ambient pressure, it is shown that for valved pulsejets, the combustion chamber pressure is only decreased by expansion waves from exhaust pipe. But for valveless pulsejets, the combustion chamber pressure is decreased by the expansion waves from the outlet and the inlet as well. The oxygen for the reaction is provided by the airflow from the inlet only thus the operation cycles of the valveless pulsejets rely on both inlet and exhaust pipe. With carefully designed inlets, combustion chamber, and tail pipe, valveless pulsejet size can be scaled down from 50 cm to 8 cm. Furthermore, with forced air injection, the smallest working valveless pulsejet built has a total length of 5 cm. In experiments to solve the problems of heat loss and short
residence time of small scale pulsejets, we increased combustion chamber volume and pre-heat fuel in some cases to help pulsejets to startup.

(2) From the point of view of acoustics, the traditional valved pulsejet behaves like a 1/6 wave tube and the operating frequency is a function of the exhaust pipe length and the combustion chamber volume. However, in valveless mode, the operating frequency is also a function of inlet length, but does not act as a 1/6 wave tube. Rather, the frequency scales with the inlet length raised to negative 0.22 power.

(3) With forward-facing inlets, the net thrust generated by valveless pulsejets are very low as expected. With rearward-facing inlets, the net thrust for 8 cm valveless pulsejet improves to approximately 1 N, resulting in a TSFC of 0.02 kg/N-hr.

(4) The exhaust flow of the pulsejet is dominated by the starting vortex ring. A flare at the end of the exhaust pipe can help starting vortex ring to form and increase the ring circulation. The simulation results reveal that higher ring circulations result in lower combustion chamber pressure and thus higher fuel flow rate, which increases thrust. Area ratio between flare exit and exhaust pipe, $AR$, is defined to study the effect of flare on pulsejet thrust. It is shown that when $AR=2$, the pulsejet has the longest vortex ring pinch-off time and the maximum thrust. The Formation number for various $AR$ values shows that thrust is a strong function of this parameter and the maximum thrust case occurs for the geometry with a Formation number of 3.9, which falls in the
6.2 Future Work

Extensive simulations have been done in this research. The simulation results agree well with experimental data. There are some improvements on the simulation models in the future.

(1) The modeling of valves is critical to the modeling of valved pulsejets. In this research it is modeled by specifying a boundary condition that calculates the velocity across the valves depending on the combustion chamber pressure. This calculation is based on the experimental measurement of the mass flow rate across the valves at various pressure differences. This approach can give a relatively accurate total mass flow rate entering the combustion chamber in each cycle. However, it didn’t model the deformation of reed valves and thus may not capture the delay effect caused by the valves. In the future, the interaction between solid valves and fluid may be added in the model.

(2) A more detailed combustion model with multi-step reactions could replace current single-step combustion model to improve the combustion modeling.

Thrust performance for valveless pulsejets is poor even with rearward-facing inlets. Compared with valved pulsejets, the pressure rise due to combustion is small. To use micro-scale pulsejet as a propulsion device, thrust needs to be maximized. The inlet geometry, number of inlets, and flare geometries at the inlets and exhaust pipe can be optimized to improve thrust performance.

From the vortex ring study it is evident that there is a close relationship between

range calculated by Ghraib et al.
vortex ring pinch-off time and pulsejet thrust. It is not clear whether the starting vortex ring itself can contribute to the total thrust generated by pulsejet. It is worthwhile to separate thrust generated by vortex rings from that of trailing jet.
7 List of References


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