Experimental Study of Rounded Ejector Inlets for Pulse Detonation Engines

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ABSTRACT

An experimental investigation is described in which thrust augmentation was measured for a variety of Pulse Detonation Engine (PDE) ejectors. This study is part of an ongoing project focused on the complete understanding of thrust augmentation of PDE driven ejectors. Prior experiments considered utilized straight ejectors with distinct lengths and constant diameters. In this experiment, an additional rounded inlet mounted on various straight ejectors was utilized to determine its effect on thrust augmentation. Measurements were taken to determine the effect on performance at different overlap positions between the detonation tube and the ejector. Higher thrust augmentation measurements were obtained with the rounded ejector inlet. Thrust increments with the rounded inlet increased as much as 39% from the baseline values. Furthermore, experiments carried out with the straight and rounded ejector inlet both indicate that thrust augmentation reaches a maximum value at a positive overlap position from which it decreases sharply as the distance is increased. It is also noted that at a zero overlap position, average thrust values all seem to drop and fall within the same range.

NOMENCLATURE

\( x \) = overlap distance between detonation tube and ejector

\( l_1 \) = ejector length 1 ft

\( l_2 \) = ejector length 2 ft

\( l_3 \) = ejector length 3 ft

\( l_4 \) = ejector length 6 ft

\( D \) = ejector outside diameter 6 in.

\( D_i \) = ejector inside diameter 5.75 in.

\( L \) = length of detonation tube 68 in.

\( d_j \) = detonation tube inside diameter 2.25 in.

\( d_o \) = detonation tube outside diameter 2.75 in.

\( k \) = spring constant 37 lbf/in

\( NR \) = ejector nose radius 0.5 in.
INTRODUCTION

Pulse detonation engines (PDEs) present a key technological advancement in today’s aerospace industry due to its high combustion efficiency and overall improved performance over conventional aircraft engines. Detonations have proven to be an extremely efficient means of burning a fuel/oxidizer mixture in comparison to traditional deflagration methods of combusting fuels. The current interests in pulse detonation engines have also revived interest in pulsed ejectors, since they may increase thrust. This supposition is based on the few experiments that have been reported in which thrust augmentation from a pulsating and other sources of unsteady flow were measured [1-5]. It is projected that pulse detonation engines will be able to operate with higher propulsive efficiency, reduced hardware complexity and lower total operational cost when compared to current propulsion devices such as scramjets and gas turbines.

Industry and academic research today is focused on the experimental study and development of pure PDE systems. Current studies conducted here at The Pennsylvania State University present different innovative applications that involve the incorporation of a PDE as a component in a hybrid Pulse Detonation/Turbofan Engine. This project is part of a NASA three year contract on the study of PDE driven ejectors that would be applicable to hybrid aircraft engine concepts. It has been reported that the incorporation of an ejector would be intended for applications that would replace the high pressure compressor and high pressure turbine sections of the core of a high bypass turbofan engine [6]. Therefore, one of the main advantages of the PDE-ejector system is the reduced cost due to the elimination of expensive components with resulting reduced engine weight, along with improved specific fuel consumption and specific power inherent in the incorporation of a PDE component [6].

Additionally, the fabrication and use of rounded ejector inlets is also part of the complete development and study of the PDE driven ejector system. The present paper presents various designs of different profile ejector nose radii based on scaling and sizing of the used jet diameter and ejector diameter. There have been mixed results in prior outside studies of unsteady ejector performance with varying nose radii. For example, using a pulsejet driver, Paxon reported that the ejector nose radius does have a strong effect on thrust augmentation [2]. Using a resonance driver, Paxon additionally reported that nose radius does not play any statistical role in thrust augmentation [3]. Both of these drivers provided suitable sources for the investigation of unsteady ejector performance since the nature of both drivers are unsteady. A third report conducted by Paxon concluded that the ejector diameter for which optimal thrust augmentation obtained is directly linked to the geometric size of the vortex ring, and that the vortex ring size is geometrically related to the jet diameter [3]. Therefore, an experimental study for thrust measurements with various sizes of ejector nose radii that encompasses the geometric size of the vortex ring created is clearly needed.

BACKGROUND

Ejectors are fluid pumps that are used to entrain secondary flows using a primary flow. For propulsion applications, this entrainment of flow can augment thrust compared to that generated by the primary flow alone and thereby increase performance [1]. Furthermore, the addition of a smooth rounded surface at the inlet of the cylindrical ejector will serve as an airfoil
and will further augment the air entrained into the ejector. Based on previous experiments performed by Paxon, thrust augmentation increment factors no greater than two are expected [2].

Air-breathing engines can be classified according to the type of transient or non-transient combustion process employed in the device [7]. Since the combustion process encountered in PDEs is cyclic, it can be characterized as an unsteady process. Additionally, propulsive systems can be also distinguished either as involving deflagration or detonation combustion processes. To better understand the innovative idea and the power affiliated with PDEs, it is imperative to understand a few preliminary concepts. The following discussion will attempt to describe these concepts.

**Deflagration**

A deflagration combustion process occurs when a mixture of oxidizer (such as oxygen or air) and fuel burns subsonically at a nearly constant pressure. One of the primary characteristics of deflagration is that the flame travels at a significantly lower speed than the speed of sound. Deflagration speeds normally encountered for most hydrocarbons/air mixtures are of the order of one or more meters per second. The propagation of a deflagration flame is governed by the laminar or turbulent diffusion of unburned gases ahead of the flame and burned gases behind the flame [7]. By utilizing this concept and causing an air/fuel mixture to deflagrate in an enclosed space, it is possible to harness the pressure generated to perform work. In general, deflagrations produce small divergences in pressure and are therefore normally treated as nearly isobaric processes.

**Detonation**

A detonation is a form of gas “explosion” that results in rapid reactions that create a pressure wave that travels at supersonic speeds. Unlike deflagration, a detonation does not require confinement or obstructions in order to propagate at high velocity. A detonation is defined as a supersonic combustion wave, meaning that the detonation front propagates into unburned gas at a velocity higher than the speed of sound in front of the wave. The gas ahead of a detonation therefore remains undisturbed by the detonation wave. Typical detonation velocities encountered for most hydrocarbon/air mixtures are 1500-2000 m/s [8]. Detonations produce vastly higher pressures than the simple process of deflagration. This peak pressure generated in the engine can be utilized to obtain higher levels of thrust than from an engine with a deflagrative combustion process. In general, due to the high speed nature of a detonation wave, detonations closely approximate a constant volume combustion process [7].

**Unsteady Engines**

Engines such as the pulse detonation engine or pulse jet engines are solely based on unsteady combustion operation. Combustion in these engines is very similar and occurs in a cyclical manner producing unsteady thrust. To obtain useful parameters, cycles are repeated with a constant frequency yielding average thrust measurements. Unlike unsteady engines, steady state engines are characterized by a continuous, constant pressure, deflagration process [7]. Most engines used in industry today can be classified as such.
PDE Cycle Operation

The pulse detonation engine consists of long round tube, with a specific diameter in which the detonation and the cycle operation takes place. This tube is closed at its detonation initiation position and open at its trailing end. Previous experiments performed on open and closed end pipes, have shown that the highest flame speed was observed when the gas was ignited in the closed end and the other end was open [8]. In this case, the gas ahead of the flame was pushed through the pipe and a lot of turbulence was generated.

Engine operation can be described by the four major processes that occur during each of its operating cycles. The four major processes are repeated every time an engine cycle is initiated.

These steps are as follows (See Figure 1):

1. Filling of the detonation tube with fuel/oxidizer mixture
2. Detonation is initiated through a spark at the closed end of the tube
3. Detonation wave propagates through the tube and exits at the open end
4. Blowdown of the burned products

In summary, the combustion chamber is completely filled with the fuel/oxidizer mixture through the operation of a valve system. The valve system is calibrated such that the chamber is completely filled at the time of ignition. Once this condition is met, the valves are closed and an ignition source is utilized to ignite the combustion mixture. The initial waves rapidly transition to a detonation wave via a process called DDT (Deflagration to detonation transition).

The third major step consists of the propagation of the detonation wave. The detonation wave travels down the combustion chamber at a supersonic velocity raising the pressure of the gases in the tube and creating a pressure and temperature difference between the region ahead of the detonation wave, behind the wave and the closed end of the combustion chamber. This behavior is caused by an expansion zone created between the closed of the detonation tube and the detonation wave [7].

Lastly, the products are exhausted out of the combustion chamber and into the atmosphere by a series of rarefaction (expansion) waves which propagate back into the tube. The expansion waves travel back into the chamber at the speed of sound of the gas mixture [7]. This expansion process accelerates the fluid towards the exit, lowering the pressure back down to ambient pressure. This combustion process repeats itself with a series of compression and expansion waves yielding the unsteady nature of the engine. This pressure differential created by the detonation wave produces unsteady thrust. As the cycle is repeated at a constant frequency, 10 to 100 Hz, an average thrust useful for propulsion is generated [9].
METHODOLOGY

Engine Configuration

The engine detonation tube is made of high strength aluminum with 2.25 inner (dj) and 2.75 inch outside (do) diameters. Total length of the detonation tube from the injector face to the tube exit is 68 inches (figure 2). An impinging jet injector is utilized to introduce the required mixture into the detonation tube. A spark plug and an ignition system are used in order to ignite the propellants and begin the PDE cycle. The time frame for each of the 100 ms (10 Hz) cycles is outlined as follows. The oxidizer mixture is injected into the detonation tube for 12 ms. Propellants are then delivered for 62.7 ms into the detonation tube. The fuel and oxidizer flow rates are 11.2 and 71.0 g/s respectively. After the detonation tube is filled to its precise condition, the propellant valves are closed and the mixture is ignited [6].

Thrust Measurement System

Average thrust measurements were recorded through the use of a calibrated spring damper measuring system. The detonation tube is mounted on a solid table top by means of two frictionless rails. A thrust block with a tension spring (k=37 lbf/in.) is connected to the downstream end of the PDE/ejector tube assembly. The thrust block provides an offset load of 5 lbf utilized to keep the spring in tension (Forces lower than this value will not allow the system to move). A hydraulic damper and a linear voltage displacement transducer (LVDT) are connected to the injector assembly end of the detonation tube. The purpose of the damper is to decrease the oscillation of the system in order for the engine to reach steady state at a faster rate. The LVDT is utilized to measure the displacement of the engine as it is operated. Figure 2 gives details of the apparatus.

For accuracy, engine calibrations were performed before and after each experiment was operated and thrust measurements were taken. Calibration of the engine was conducted by measuring the displacement of the assembly for a range of forces. A frictionless pulley weight arrangement system provides the known applied forces to the system and is utilized for calibration. Calibration analysis shows that due to frictional losses, the system does not behave completely linearly. Therefore, an offset value is seen in the numerical analysis and a polynomial regression equation is utilized to predict the thrust as it varies with time.

Experimental

In order for us to gather useful, comparable data points it is imperative that we record baseline experiments with the PDE set up only. Having this information gives us reference points from which to compare our straight and rounded ejector inlet thrust augmentation (Figure 3). Baseline experiments for time-averaged thrust were conducted in multi-cycle mode at an operating frequency of 10 Hz and 80 cycles. Time averaged thrust was recorded using a high fidelity spring-damper thrust measurement system which was calibrated repetitively as needed. Baseline experiments were operated using ethylene (C₂H₄) as the fuel and oxygen/nitrogen with equal molarities as the oxidizer. Ethylene was selected as a fuel due to its availability and high volatility properties with oxygen and nitrogen combinations [6].
Various overlap positions of the ejector with respect to the detonation tube were attempted to characterize engine performance. To normalize our parameters, we referred to these overlap position as x/dj, with x being the axial distance from the detonation tube exit to the ejector inlet and dj being the inner diameter of the detonation tube. As a convention, we selected a positive x/dj factor to represent overlapping of the engine and the ejector in the experiments and negative x/dj factor to represent separation.

For the present study, three different ejector inlets were designed and fabricated based on previous experimental and theoretical results analyzed in multiple reports by Paxon [1,4,5]. The nose radii selected were 0.25, 0.50 and 0.75 in. This paper presents measurements from additional experiments with the objective to observe characteristics of the rounded ejector inlets through the use of average thrust measurements. All inlets have a standard length of 3 inches that do not interfere with any other component once mounted on the ejector (Figure 3). In addition, thrust augmentation measurements were made for various overlap distances yielding a complete understanding of the experiment. Figure 3 clearly illustrates the straight and rounded ejector inlet configurations.

Parameters measured in previous experiments focused on the thrust augmentation characteristics of the PDE and the PDE/Straight Ejector Inlet arrangement with distinct ejector diameters at various overlap positions. Optimized results from these experiments have shown that by using a 6 in. outside diameter ejector, a maximum average thrust increment of 24% can be achieved (Figure 4) [6]. Based on these results, a constant 6 in. straight ejector diameter was utilized as the baseline geometry for the rounded ejector inlets.

RESULTS AND DISCUSSION

The experimental procedure involved running the PDE tube several times for it to reach thermal equilibrium. Baseline measurements were then recorded. Constant 6 in. straight ejector diameters of various lengths were utilized due to their well characterized performance (Figure 4). Results reported here are for the 0.5 in. rounded inlet ejectors. The ejectors were then moved over a full range of negative and positive x/dj values and thrust measurements were recorded as needed.

Straight Ejector Inlet Measurements

Previous experiments conducted have shown that thrust augmentation seems to increase as the positive overlap distance between the ejector and the detonation tube is enhanced. In these experiments, the longer 6 ft ejector yielded the highest percent of thrust augmentation at a positive overlap position of x/dj=9.33. It should be observed that these measurements are consistent with the earlier measurements (made in 2003) for the 6 ft ejector (Figure 5).

Figure 5 shows a compiled summary of thrust percent augmentation for all of the constant diameter ejector configurations. The variables in the experiment were the length of the ejector tube as well as its overlapping position with respect to the detonation tube. All the ejectors give lower performance at the x/dj=0 overlap location. Average thrust augmentation values for the 2, 3, and 6 ft ejectors lengths fall nearly on the same range of points at the x/dj=0 position. The 1 ft
ejector has no effect on the thrust augmentation when positioned at x/dj=0. Values in the range of x/dj=0 to x/dj=-1 have a moderate increase in thrust measurements. It is observed that for all ejector parameters less than x/dj=-1 there is a sharp continuous decrease in the thrust obtained. Thrust augmentation increases drastically as the x/dj value increments above zero. These values all seem to reach a maximum limiting point and sharply decrease after this point has been reached.

**Rounded Ejector Inlet Measurements**

The proceeding series of experiments were performed with the 0.5 in. rounded ejector inlet design. The other two designs have been fabricated but were not utilized in this set of experiments due to time issues. Measurements at different overlap positions were taken. The following graphs show the experimental work accomplished with the rounded inlet. The experiments were done with the 1, 2, 3, and 6 ft ejectors with constant 6 inch outside diameter.

Figure 6 shows the thrust augmentation achieved using the 1 ft long ejector. Thrust decreased at values lower than x/dj=-1. For x/dj values=-1 to 1, the average thrust seemed to stay nearly constant reaching a peak value at x/dj=1 of 18.8%. Once this peak value was obtained thrust decreased steadily to x/dj=2 where it sharply dropped to a value of 5.9%. Figure 7 shows the thrust augmentation obtained using the 2 ft long ejector at various x/dj values. No values were taken with the ejector tube positioned downstream of the PDE. A maximum thrust augmentation of 28% was obtained at an x/dj point of 3.99.

Thrust augmentation for the 3 ft ejector is shown in figure 8. Average thrust slightly increased from x/dj values of 0 to -1. For values of x/dj less than -1, the thrust declines sharply as in the other cases. Similarly, thrust augmentation reaches an overwhelming peak value of nearly 40% at x/dj=3.99 and decreases after it reaches this point. It is worth noting that the maximum thrust augmentation for previous experiments performed without the rounded inlet yield a 24% maximum thrust augmentation for 6 ft ejector. Having the rounded inlet mounted provides a higher thrust augmentation with a shorter overall ejector length.

Figure 9 clearly shows that a maximum thrust augmentation value of 37% was obtained utilizing a 6 ft ejector at an overlap position of x/dj=9.33. This peak value was obtained at a higher overlap parameter of x/dj 9.33 than the 3 ft ejector x/dj=3.99. As expected, the curve reaches a critical maximum value and steadily decreases thereafter. However, the thrust augmentation does not decrease much when its overlap position changes from x/dj=0 to -1. Once x/dj decreases below -1, the thrust augmentation percent value decreases sharply. However, the curve seems to stay nearly constant as the overlap is increased above 9.33.

A summary of all the PDE/ejector inlet configurations studied are shown in figure 10. The highest thrust augmentation was found to be at an x/dj factor of nearly four. This is in accordance to our previous observation that optimal thrust augmentation would be highest at a positive overlap position rather than away from the detonation tube. In addition, the 3 ft ejector has now achieved the highest percent thrust augmentation of 39% from the baseline value. Previous thrust measurement experiments conducted without the rounded ejector inlets have
given the 6 ft ejector the highest thrust augmentation percentage out of all the ejectors. Thrust percentages seem to decrease at x/dj=0 and nearly stay constant until x/dj=−1 is reached. In addition, the 2 and 3 ft ejectors give nearly identical thrust values for x/dj=0, 2, and 4. Unlike previous experiments, the 1 ft ejector gives a positive augmentation value of 17% at x/dj=0. Thrust augmentation percentage values for all the ejectors nearly converge at x/dj=0. The 2 and 3 ft ejector give identical increments of 22% while the 1 and 6 ft ejectors differ by 5% accordingly. This phenomenon was also observed in previous PDE experiments conducted with the straight ejector inlet where the 2, 3, and 6 ft ejectors gave nearly equal augmentation measurement of 6%.

Figure 10 also presents experimental results obtained by Rasheed et al.[9]. The objective of this presentation is to compare both experimental configurations due to their similar geometries and experimental procedures [9]. Rasheed et al.’s ejector diameter, rounded ejector inlet, inner jet diameter and ejector length are 6, 0.5, 2 and 9 in. respectively [9]. It can be directly observed that Rasheed et al.’s rounded ejector seems to give higher thrust augmentation values at negative x/dj values, having a peak performance of 15% at x/dj=−2. As the overlap distance approaches x/dj=0, the thrust augmentation decreases and falls into the negative region after the x/dj increments above 0. Their 1 ft ejector and the 1 ft ejector utilized in our experiments coincide only at approximately x/dj=−1, both giving thrust augmentation values of 12% at that position. Other current results with the same configuration at different overlap positions differ considerably from their data. It should be noted however, that for their experiments hydrogen (H₂) and air were used as the fuel and oxidizer. This chemical difference in fuel from ethylene (C₂H₄) could serve to explain the discrepancies between the two sets of results. Another source for discrepancy in the measurements might be the fact that for their experiments continuous flow of air in the detonation tube was utilized which could cause the engine to mimic steady state behavior in between cycles.

**CONCLUSIONS**

The results presented here provide credible information on the amount of thrust augmented by the use of various ejectors geometries. Furthermore, the use of a rounded ejector inlet increased the average thrust by as much as 39%. It can be directly observed that a higher thrust augmentation can be obtained for positive overlap positions rather than negative positions.

<table>
<thead>
<tr>
<th>Ejector</th>
<th>Straight Ejector</th>
<th>Rounded Ejector</th>
<th>Increase</th>
<th>x/dj</th>
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<td>3.2</td>
<td>18.8</td>
<td>15.6</td>
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<tr>
<td>2 ft</td>
<td>11.7</td>
<td>27.7</td>
<td>16</td>
<td>3.99</td>
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<td>17.1</td>
<td>39.1</td>
<td>22</td>
<td>3.99</td>
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<tr>
<td>6 ft</td>
<td>25</td>
<td>37</td>
<td>12</td>
<td>9.33</td>
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It is once again observed that our results differ from the results published by Rasheed et al. [9]. Their peak performance was obtained with a short ejector positioned at a point further away from the detonation tube [9]. Our results for the straight and rounded inlet ejectors are qualitatively
similar, and both these sets of results differ from Rasheed et al.’s result. These differences may be due to the fact that the fuel types are not the same between the two sets of experiments. Furthermore, the valved air flow for our experiments versus continuous airflow for their experiments may also cause a systematic difference between the two sets of experiments.

REFERENCES

Figure 1. A PDE Engine Cycle. U\textsubscript{CJ}: Chapman-Jouguet Detonation Velocity

Figure 2. Schematic of PDE-Ejector set up on thrust stand.

Figure 3. Side view of straight and rounded ejector inlets
Figure 4. Thrust Augmentation for various straight ejector diameters and overlap positions

Figure 5. Thrust Augmentation for Straight Ejector Inlet
Figure 10. Thrust Augmentation for Rounded Ejector Inlet

Summary of % Thrust Augmentation for Ejectors
(0.5 in radius inlet), dj = 2.25 in, D/dj = 2.67