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Thrust Augmentation Measurements Using a Pulse Detonation Engine Ejector

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March 2003

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1. Introduction

Pulse detonation engine (PDE) technology is currently receiving a great deal of consideration because of its potential for high efficiency combustion performance with reduced hardware complexity [1-2]. Although most of the current research efforts are focused on resolving the barriers to a pure PDE system, there are equally worthy options that involve the incorporation of a PDE as a component in hybrid engine concepts. The present NASA GRC funded three-year research project focuses on the study of a PDE driven ejector that would be applicable to a hybrid Pulse Detonation/Turbofan Engine. The 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. The objective of the present study is to characterize the thrust augmentation achievable with a PDE-ejector and thus provide critical experimental data from which to assess the performance enhancements possible with this technology.

The major potential advantages of the PDE-ejector as envisioned here include reduced costs due to the elimination of expensive compressor and turbine components with resulting reduced engine weight, along with improved specific fuel consumption and specific power inherent in the incorporation of a PDE component. There is currently insufficient data on the performance of such an ejector system to allow further development. Some of the key issues can be resolved if suitable measurements of the thrust augmentation were available over a suitable parameter space. Thus, at the present time the hybrid PD/Turbofan engine is at a Technology Readiness Level (TRL) of 2 and the present research intends to increase PDE-ejectors to TRL 3 through the provision of critical experimental data that further defines the operational potential of this novel technology.

The current research project on thrust augmentation experiments (NAG3-2657) was officially awarded to Penn State on January 30, 2002. The progress made on the project during the previous eight months in described in this report.

2. Key Accomplishments in FY02

The following tasks have been completed during the first eight months of the project.

- A thrust stand for measuring average thrust for multi-cycle operation of a detonation tube has been designed and implemented.
- The average thrust for an existing 1.3 in. diameter detonation tube has been measured and analyzed for ethylene as the fuel and a mixture of oxygen and nitrogen as the oxidizer.

- Based on these initial measurements, a 2.25 in. diameter detonation tube has been designed and fabricated as the driver for the PDE-ejector thrust measurement experiments. The modular design of the system will allow experimentation to assess the effects of ejector geometry (diameter, length and shape) on thrust augmentation. The ejector section for the experiment has been designed and fabrication is near completion. Experiments will commence in the very near future.

2.1. Thrust Stand Description

A thrust stand for measuring average thrust for multi-cycle operation of a detonation tube has been designed and implemented. A schematic of the system is shown in Fig. 1. The thrust stand features a solid table top on which the detonation tube is mounted on frictionless rails. A thrust block with a spring (k=14.4. lbf/in.) is attached to the injector assembly end of the detonation tube. Calibration of the assembly was conducted by measuring the displacement of the assembly for a range of forces. A force gage was used to supply a known force to the system, whereas a linear voltage displacement transducer (LVDT) was used to measure the displacement. The calibration curve for the system for the 1.3 in. diameter detonation tube (described in the next section) is shown in Fig. 2. The calibration results show that due to

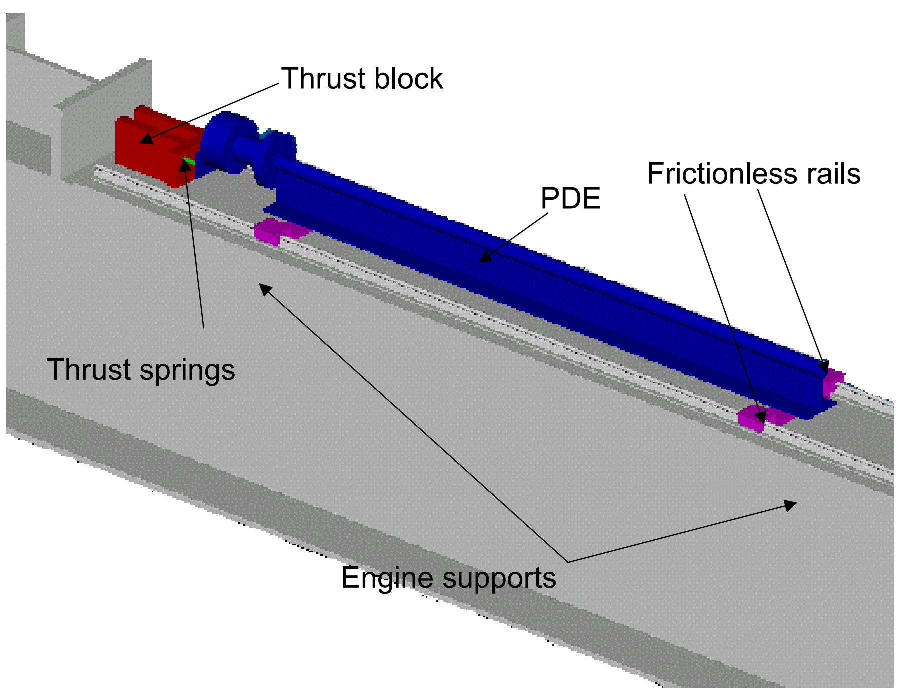


Fig. 1. Schematic of thrust stand setup.

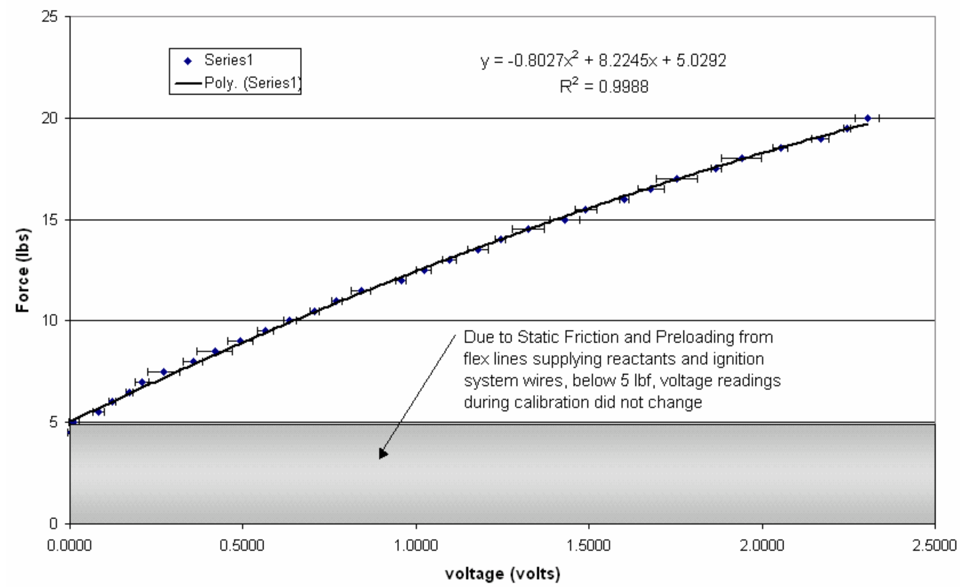


Fig. 2. Calibration showing applied force versus voltage measured for LVDT transducer.

frictional forces, and stiffness of the flex supply lines and ignition system, the system is not completely described by Hooke's law. For forces lower than about 5 lbf, the system does not move. However, for forces greater than 5 lbf, the measured displacement allows the applied force to be measured.

The theoretical response of the system was also modeled. For the modeling, the system was considered to be frictionless. The damping of the system was unknown, but for the modeling, the damping response was assumed to be under-damped. Response outputs were simulated for a range of damping conditions. Matlab-Simulink was used to model the following displacement equation for a 10 Hz periodic force, $F(t)$ with an average of 6 lbf, a mass, m, of 100 lbm (system mass) and a spring constant, k, of 14.4 lbf/in.

$$F = m\left(\frac{d^2x}{dt^2}\right) + c\left(\frac{dx}{dt}\right) + kx$$

The applied force, $F(t)$, was constructed to mimic the time history of expected detonations for 10 Hz operation. The time response results for the calculations are shown in Fig. 3 for a range of damping coefficients, c, from 0.85 to 1.75. In each of these individual graphs the abscissa represents time in seconds, whereas the ordinate represents the calculated force response (i.e. $kx(t)$). The results show that steady state displacement (and therefore, thrust) is achieved within 2 s of operation irrespective of the actual damping coefficient. Comparison

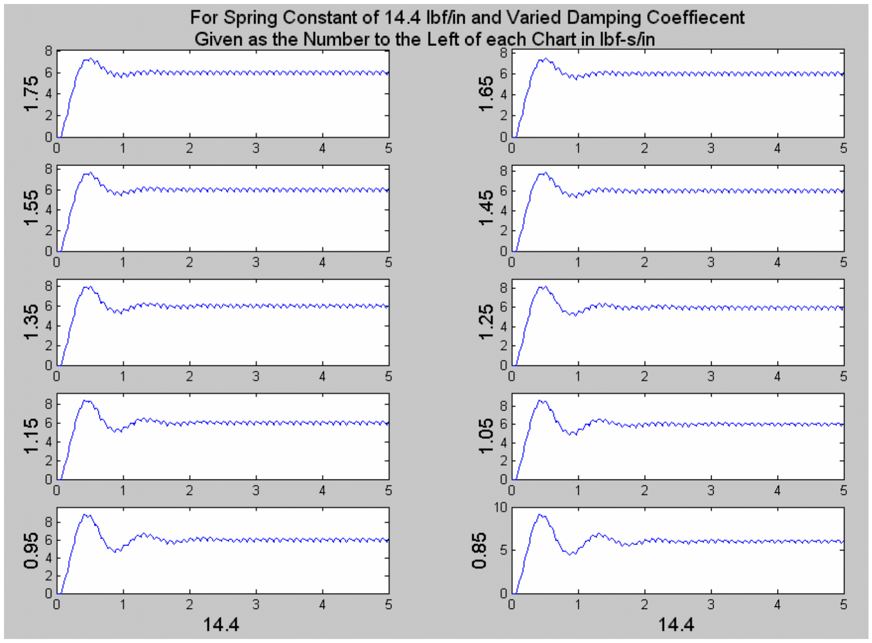


Fig. 3. Calculated thrust response results. For each trace, the abscissa represents time (s), whereas the ordinate represents force response (lbf).

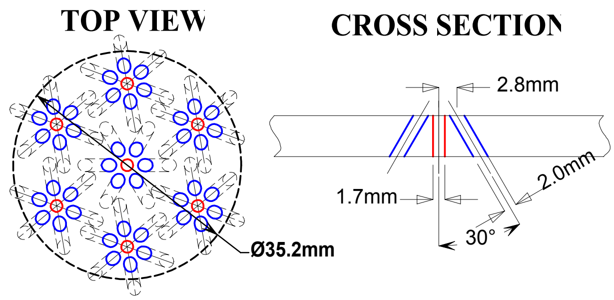
with detonation tube firing results (presented later) indicates that the damping coefficient of the system is about 1.5 lbf-s/in.

2.2. Thrust Measurements for 1.3 in. Diameter Detonation Tube

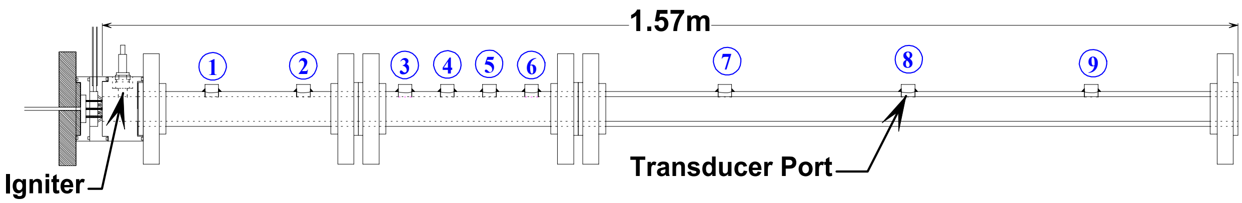
An existing detonation tube with an internal diameter of 1.3 in. was used for the initial average thrust measurements. A picture of the detonation tube, the injector used for the setup and a schematic showing high-frequency pressure transducer locations are shown in Fig. 4. For these experiments, ethylene (C_2H_4) was used as the fuel and a mixture of oxygen and nitrogen (O_2+$0.5N_2$) was used as the oxidizer. The equivalence ratio was targeted to be 1.1. High speed Valvetek valves were used to control the injection timing. For the results discussed next, 30-40 cycles at 10 Hz operation constituted a single firing. The fill time for each cycle was set to be between 70-80 ms.

Pressure measurements made near the head end of the detonation tube (Port 1, Fig. 4(c)) using a high-frequency pressure transducer are shown in Fig. 5. The top graph shows the peak pressures realized for individual detonations. The pressure traces for two consecutive detonation events during the firing are magnified in the bottom section of the figure. These results are typical of multi-cycle detonation tube operation.

(a) Image of detonation tube



(b) Impinging jet injector



(c) Detonation tube schematic.

Fig. 4. Detonation tube used for average thrust measurements.

The corresponding thrust response from the displacement measurements is shown in Fig. 6. Results are shown here for two firings of 35 and 40 cycles, respectively. As mentioned earlier, the system does not respond to forces less than about 5 lbf due to static friction and preload from flex lines used for supplying propellants, and ignition system wiring. However, the results show that the average thrust for the multi-cycle firing is reached within 2 s (i.e. 20 cycles) of the start of the firing. Based on these average thrust measurements, the mixture based I_{sp} for the firing is about 130 s. Cooper et al. [3] carried out single-shot PDE thrust measurements for the same propellant combination (i.e. C_2H_4, O_2 and N_2) using a pendulum mechanism. Their I_{sp} results for $C_2H_4/(O_2+0.33N_2)$ and $C_2H_4/(0_2+0.57N_2)$ mixtures at an equivalence ratio of one are 162 and 150 s, respectively. The current results of I_{sp}=130 s for $C_2H_4/(0_2+0.5N_2)$ at an equivalence ratio of 1.1 agrees qualitatively with their results.

The thrust measurements described here for the 1.3 in. diameter detonation tube demonstrates that steady state thrust can be accurately measured for multi-cycle operation of a PDE or PDE-ejector system. In the next sub-section, the PDE-ejector system that has been designed for this project is described.

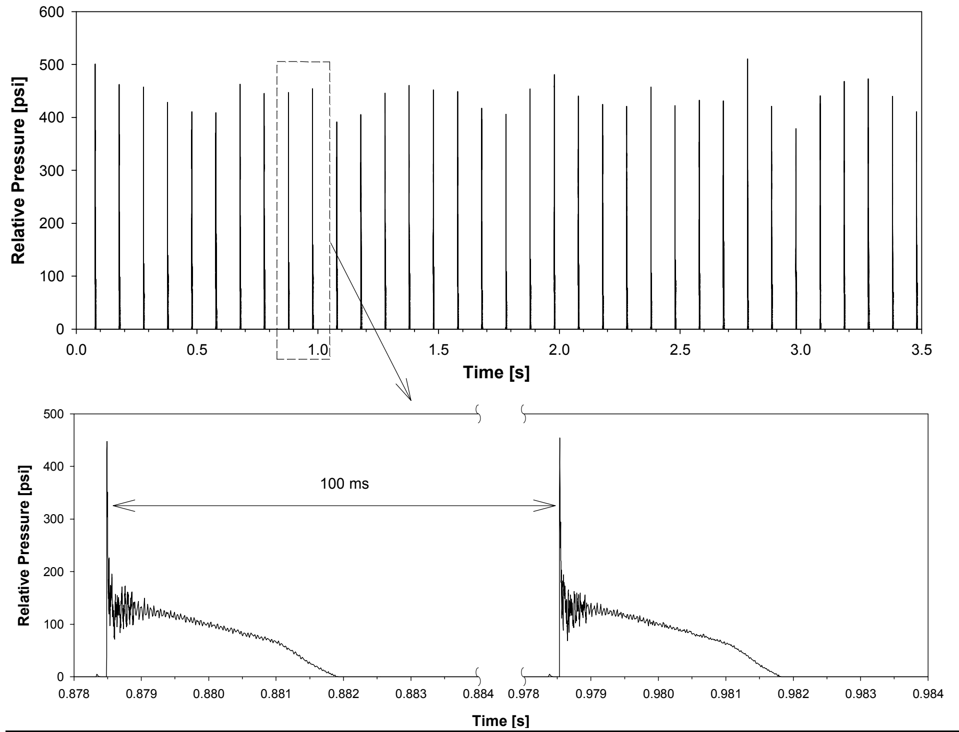


Fig. 5. Pressure measurements near injector end of detonation tube.

2.3. PDE-Ejector Description

The existing 1.3 in. diameter detonation tube cannot be used for the PDE-ejector experiments since the flanges and pressure ports would interfere with the ejector part of the setup. Based on these considerations, design of a completely new PDE-ejector system was

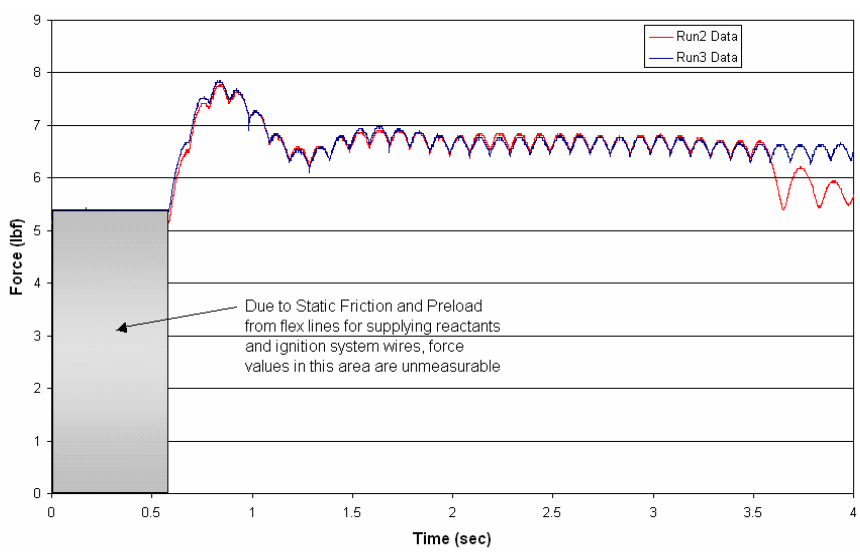
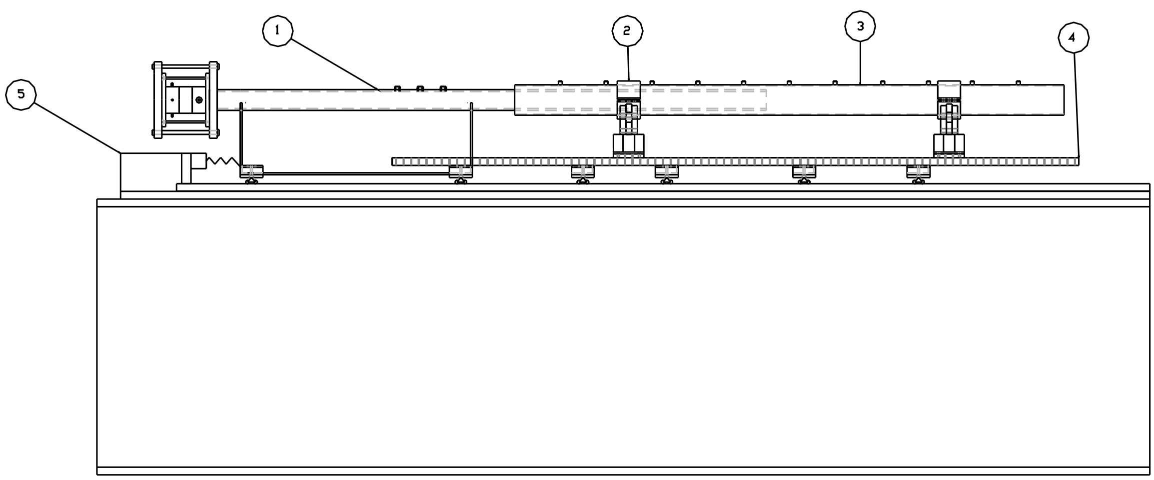


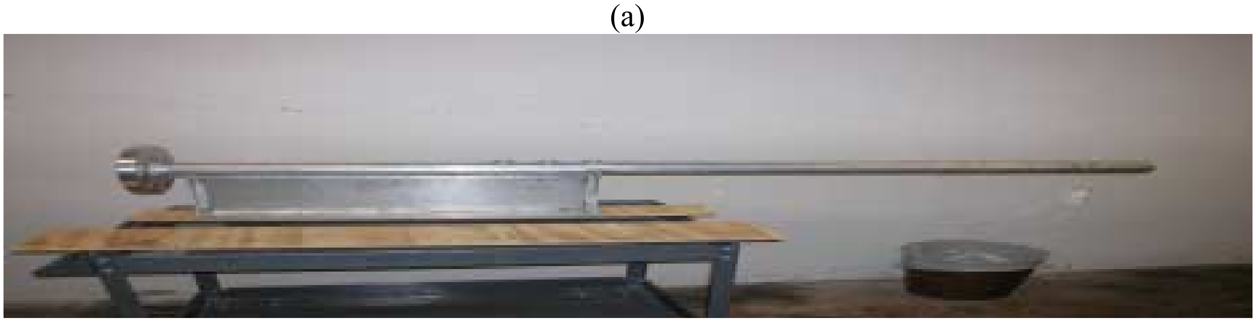
Fig. 6. Thrust measurement results for two firings of 35 and 40 cycles, respectively.

undertaken. A larger detonation tube with an inner diameter of 2.25 in. was chosen for this geometry to increase the expected average thrust level (~18 lbf) at the same operating conditions as described earlier (viz. 10 Hz operation with $C_2H_4/(0_2+0.5N_2)$ propellants at 1.1 equivalence ratio). The higher thrust level will provide greater accuracy in the thrust measurement.

A schematic of the PDE-ejector design is shown in plate (a) of Fig. 7. A picture of the fabricated detonation tube (ID and OD of 2.25 in. and 2.75 in., respectively) is also shown in the same figure. Additional detailed drawings of the setup are included in the appendix. The tube is six feet in length, with 3 ports located at 3 in. intervals in the center part for pressure transducer instrumentation. Pressure transducers at these positions will be used to verify that detonations occur in the main tube. Propellants for the detonation tube will be introduced through the impinging jet injector shown in Fig. 8. Flow control will use four high-speed Valvetek valves,

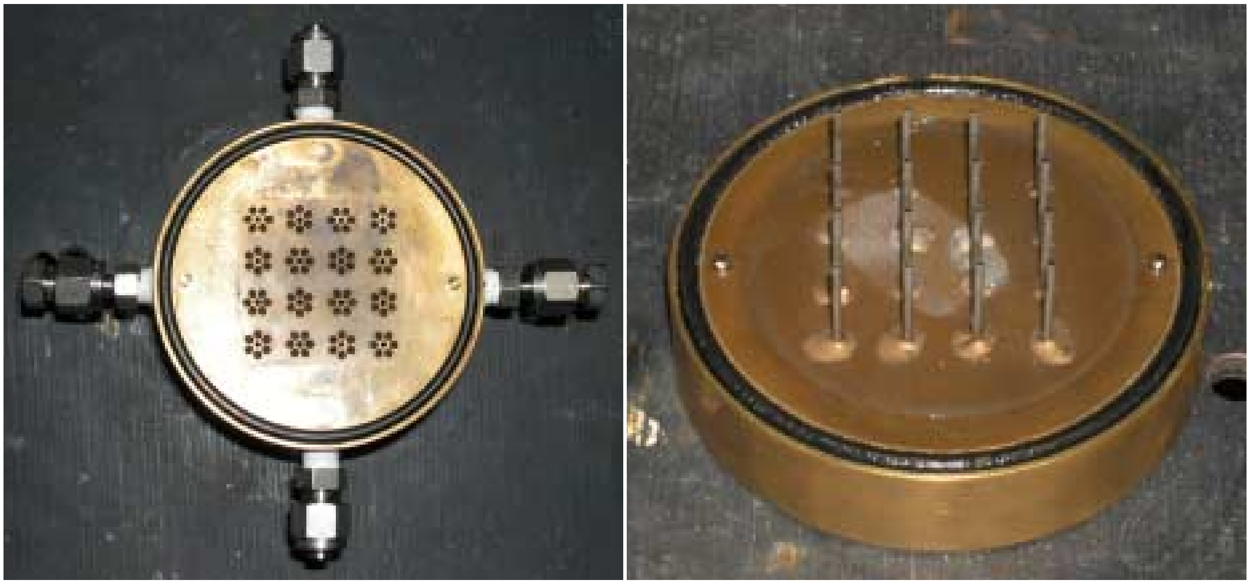


(a)



(b)

Fig. 7. (a) PDE-ejector schematic, (b) Image of 2.25 in. diameter detonation tube.



(a) (b)

Fig. 8. Injector features 16 fuel-centered impinging jet elements. For each element, fuel is introduced through the central hole, whereas the oxidizer is introduced through six angled hole that impinge and mix rapidly with the central fuel jet. (a) Impinging jet injector face, (b) Central fuel tubes for injector.

measurements as described earlier. The ejector shroud is a tube six feet in length, with a diameter larger than that of the detonation tube. Three different diameter tube ejectors will be tested. These 0.125 in. wall thickness tubes have outer diameters of 4 in., 5 in., and 6 in., respectively, and have ports in 6 in. intervals for high frequency pressure transducers. The PDE-ejector system has been designed such that the detonation tube exit can be varied within the ejector shroud. A clamp system has been designed to accommodate the different diameter ejector shrouds. The design also features the capability of lateral positioning of the ejector shroud, a feature that allows accuracy in concentric positioning of the detonation tube with respect to the ejector shroud. The detonation tube and the ejector shroud are connected with long bars that provide rigidity to the complete system. The thrust measurement device is a rectangular bar with two free moving supports having a spring wrapped around each support.

All required hardware sections are currently in different stages of fabrication with complete installation expected within 1 month. The new detonation tube fabrication is now complete, and initial experiments will concentrate on characterizing the average thrust for PDE engine only configuration. These experiments will be completed before the ejector shroud hardware fabrication is complete.

Table 1. Timeline and Milestones.

	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Measure thrust for det. tube (1.3 in.)	■	■										
Des./Fab 2 ejector ducts	■	■										
Install det. tube in 1st ejector duct			■									
Measure thrust for det. tube/1st ejector				■								
Install det. tube in 2nd ejector duct					■							
Measure thrust for det. tube/2ndejector						■						
Des./Fab optically-accessible section							■					
Schlieren studies for straight nozzle in det. tube/duct assembly								■				
Des./Fab det. tube conv. & div. nozzles							■	■				
Schlieren studies for converging nozzle in det. tube/duct assembly									■	■		
Schlieren studies for converging nozzle in det. tube/duct assembly										■	■	
Final Report											■	■

3. Measure of Technical Performance

The technical milestones for the first year of the project are included here (taken directly from the proposal).

Year 1 (9/1/01 – 8/31/02) Cost :$100,000

Milestone 1: Determine the thrust for a stand alone 1.3-inch diameter detonation tube (2/28/02).

Milestone 2: Design and fabricate two ejector ducts for each PDE tube (2/28/02).

Milestone 3: Install and test 1.3-inch PDE in one of the two companion ejector ducts. Ducts will be instrumented with high-speed pressure transducers (5/31/02).

Milestone 4: Complete thrust augmentation measurements for the 1.3-inch PDE-ejector tube in one of the two ducts. (8/31/02).

Note that for the proposal, the expected start date was 9/1/01, whereas the actual start date was delayed by 5 months (1/30/02). In short, Milestone 3 needs to be completed by 10/31/02. As discussed earlier, technical milestone 1 has been completed and milestones 2-3 are near completion (within 1 month).

4. Proposed Schedule and Relative Progress

The timeline and milestones for the project is shown in Table 1 (taken from original proposal). As is evident from the table and earlier discussion, the current progress is on track with the proposed schedule.

5. Collaborations

Collaborations with Prof. Merkle of University of Tennessee have been on-going since the start of the program. The PDE-ejector analysis performed by Prof. Merkle will help in guiding the experiments for the full course of this three-year project.

6. Interactions with NASA Glenn Research Center's PDE Research Program

The major interactions with the NASA Glenn PDE research program have resulted through the periodic review meetings that have been held at NASA Glenn Research Center and follow up discussions. In particular, interactions have occurred with Jack Wilson, Don Paxson and Rene Fernandez. We have interacted with Jack Wilson in the area of fast actuating valves to share experiences and supplier information as we are using different systems. Dan Paxson has been very helpful in the area of the design of our ejector configuration in terms of comparison with his modeling effort. In this respect, his work has impacted us more than us impacting work at Glenn Research Center. Finally, discussions and interactions with Rene Fernandez led to his participation in the conference (and Proceedings publication) of "Advances in Confined Detonations" that was held last July in Moscow, Russia.

7. References

[1] Bratkovich, T., and Bussing, T., "A Pulse Detonation Engine Performance Model," AIAA–95–3155, 1995.

[2] Santoro, R., Broda, J., Conrad, C., Woodward, R., Pal, S., and Lee, S.-Y., "Multidisciplinary Study of Pulse Detonation Engine Propulsion," *JANNAF, 36th CS/PSHS/APS Joint Meetings* (1999).

[3] Cooper, M., Jackson, S., Austin, J., Wintenberger, E., Shepherd, J. E., "Direct Experimental Impulse Measurements for Detonations and Deflagrations,"" AIAA–01–3812 (2001).

APPENDIX: PDE-Ejector Hardware

In this appendix, PDE-ejector hardware drawings are included. The design features a PDE tube (2.25 in. diameter) with a multi-element (16) impinging jet injector. Modular design allows different size ejector tubes to be used for the experiments. Design also allows ejector tube positioning flexibility.

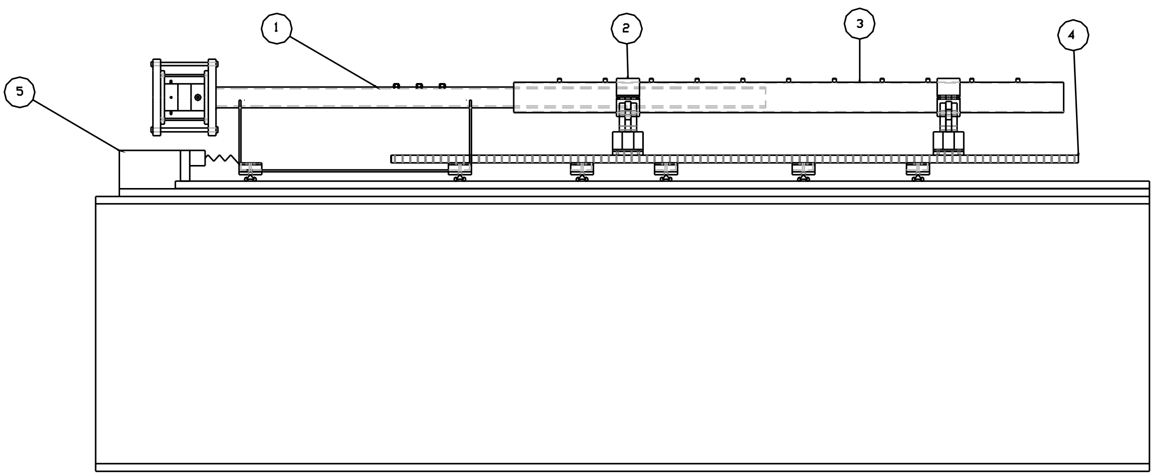


Fig. A.1. Assembly drawing of modular pulse detonation ejector system.

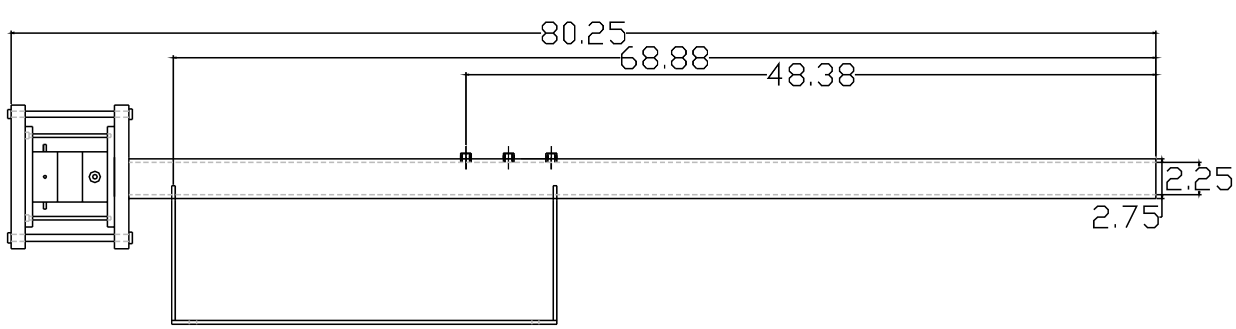


Fig. A.2. Detonation tube (2.25 in. diameter) for PDE-ejector experiments (**#1** on assembly drawing).

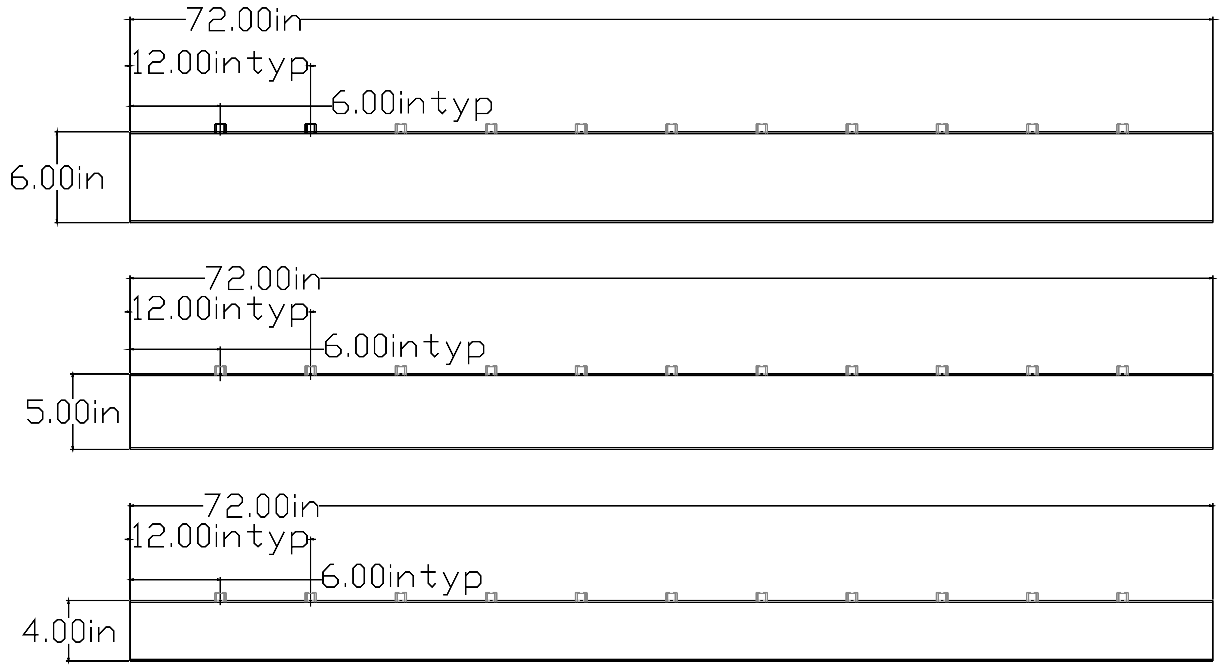


Fig. A.3. Constant diameter ejector tubes with pressure transducer ports (**#3** on assembly drawing).

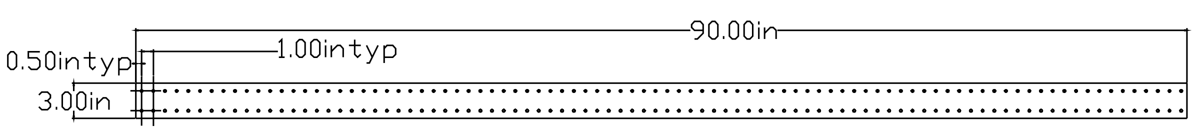


Fig. A.4. Connecting plate (**#4** on assembly drawing).

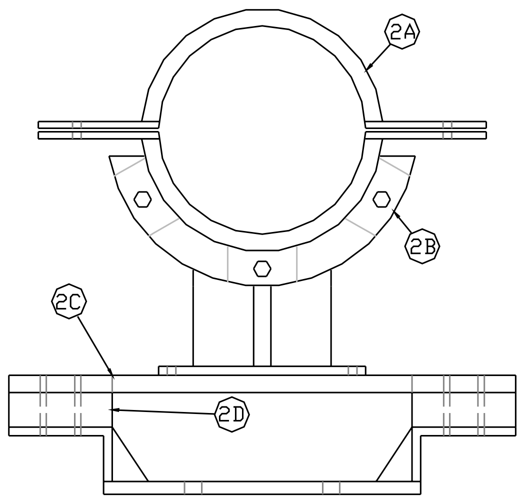


Fig. A.5. Adjustable stand for ejector tubes (**#2** on assembly drawing).

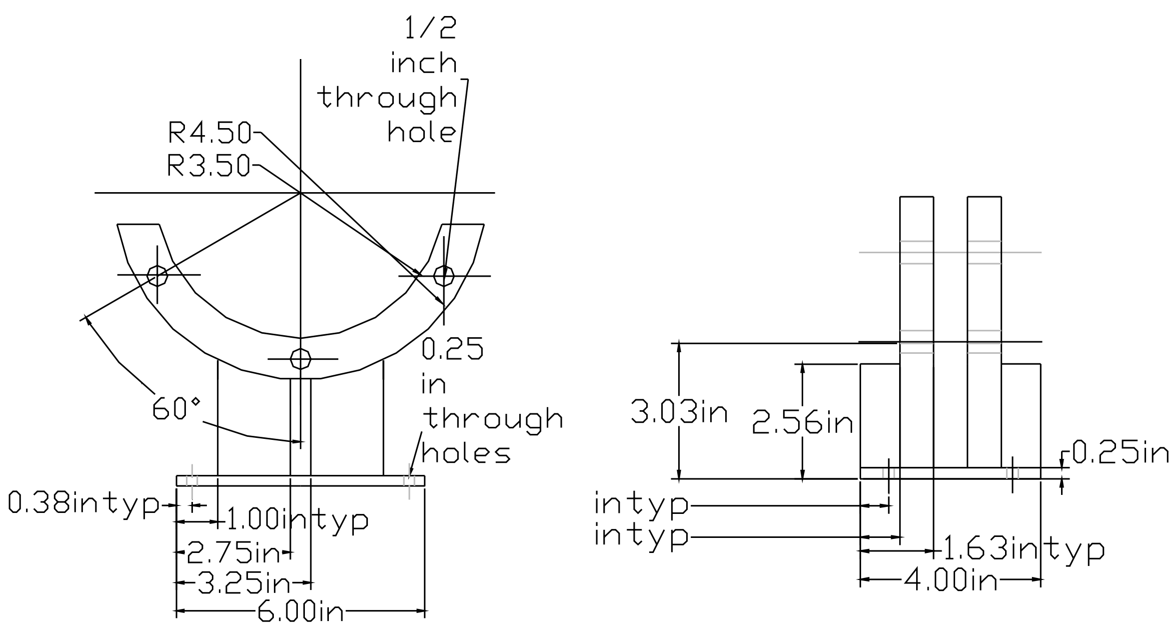


Fig. A.6. Details of adjustable stand (**#2** on assembly drawing).

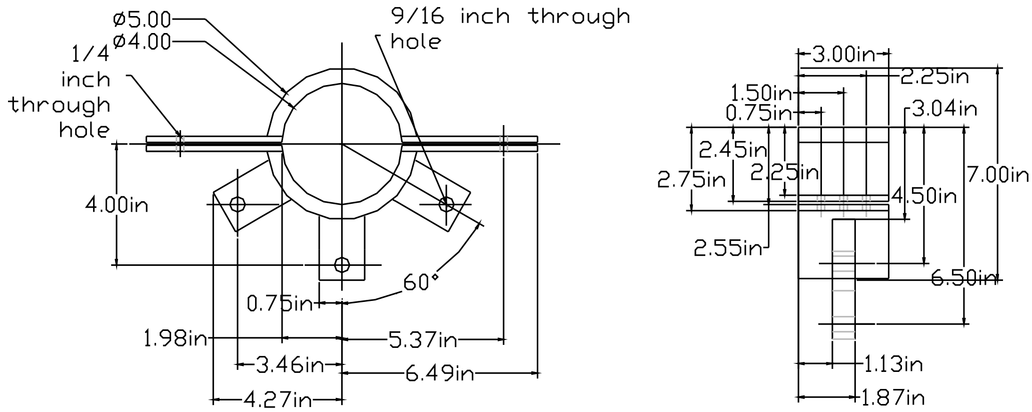


Fig. A.7. Sample clamp (**#2** part of assembly drawing).

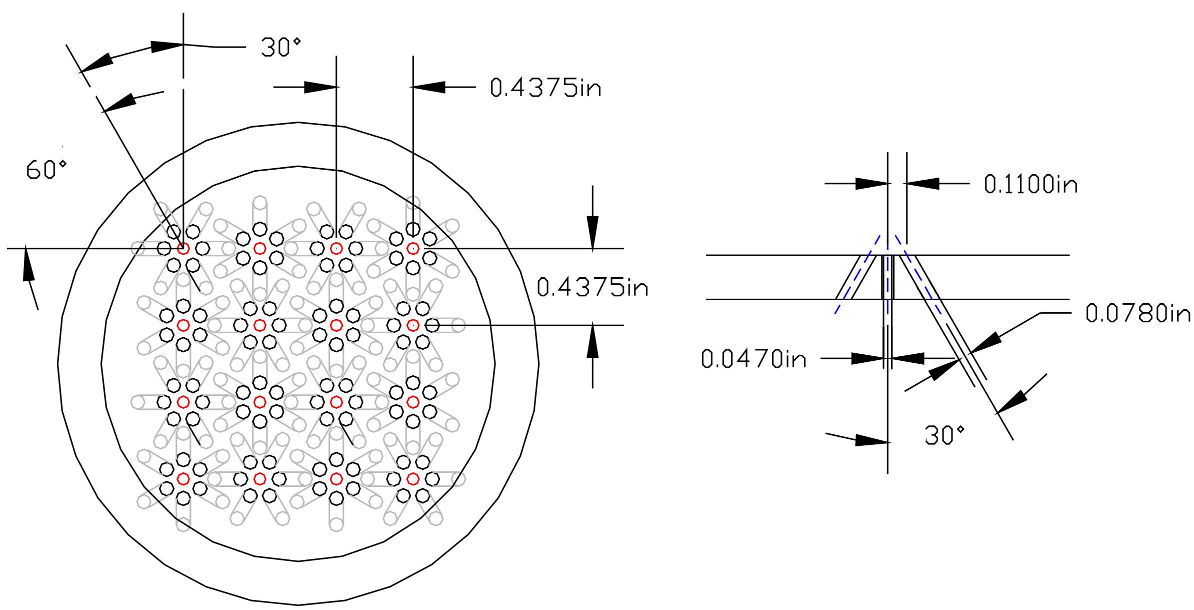


Fig. A.8. PDE injector with 16 impinging elements. Each element consists on one centered fuel hole and size angled oxidizer holes.

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13. ABSTRACT ***(Maximum 200 words)***

The present NASA GRC-funded three-year research project is focused on studying PDE driven ejectors applicable to a hybrid Pulse Detonation/Turbofan Engine. The objective of the study is to characterize the PDE-ejector thrust augmentation. A PDE-ejector system has been designed to provide critical experimental data for assessing the performance enhancements possible with this technology. Completed tasks include demonstration of a thrust stand for measuring average thrust for detonation tube multi-cycle operation, and design of a 72-in.-long, 2.25-in.-diameter (ID) detonation tube and modular ejector assembly. This assembly will allow testing of both straight and contoured ejector geometries. Initial ejectors that have been fabricated are 72-in.-long-constant-diameter tubes (4-, 5-, and 6-in.-diameter) instrumented with high-frequency pressure transducers. The assembly has been designed such that the detonation tube exit can be positioned at various locations within the ejector tube. PDE-ejector system experiments with gaseous ethylene/nitrogen/oxygen propellants will commence in the very near future. The program benefits from collaborations with Prof. Merkle of University of Tennessee whose PDE-ejector analysis helps guide the experiments. The present research effort will increase the TRL of PDE-ejectors from its current level of 2 to a level of 3.

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