



AIAA 2002-0615

INTEGRATION OF A PULSED DETONATION
ENGINE WITH AN EJECTOR PUMP AND
WITH A TURBO-CHARGER AS METHODS
TO SELF-ASPIRATE

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**40th AIAA Aerospace Sciences
Meeting & Exhibit**
14-17 January 2002
Reno, NV

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE JAN 2002		2. REPORT TYPE		3. DATES COVERED 00-00-2002 to 00-00-2002	
4. TITLE AND SUBTITLE Integration of a Pulsed Detonation Engine with an Ejector Pump and with a Turbo-Charger as Methods to Self-Aspirate				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Propulsion Directorate, Wright Patterson AFB, OH, 45433				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 15	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

INTEGRATION OF A PULSED DETONATION ENGINE WITH AN EJECTOR PUMP AND WITH A TURBO-CHARGER AS METHODS TO SELF-ASPIRATE

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Abstract

Two methods, an ejector pump and a turbo-charger, are evaluated as a means to self-aspirate a Pulsed Detonation Engine (PDE). For the experiments pertaining to the ejector pump, a pulsed detonation engine is run on hydrogen and air at frequencies up to 40 Hz, equivalence ratios from 0.5 to 1.0, and fill fractions from 0.25 to 1.0. Flow visualization is used to determine the combination of fill fraction and equivalence ratio that successfully induced a secondary flow in the ejector pump. Pressure traces at the inlet and along the ejector pump are used to understand the performance of the ejector pump. The induced secondary flow is found to be approximately triple the primary detonation flow. Fill fraction and equivalence ratio are found to affect the performance of the ejector. High fill fractions and high equivalence ratios results in an oscillatory flow at the ejector inlet. Hydrogen and air are used as the fuel and oxidizer during the experiment with the turbo-charger also. Air flow and pressure at the exit of the compressor are used to evaluate the potential for self-aspirating the PDE. By running two detonation tubes simultaneously through the turbo-charger self-aspiration is achieved. The centrifugal style turbine and compressor of the turbo-charger showed no signs of discoloration or pitting after a 25 minute self-aspiration run where the detonation tube and turbo-charger attained thermal equilibrium. Throughout the course of the testing the turbine experienced 35K plus detonation events and reached a rotational operating speed of 80K rpm.

Introduction

Because of the simplicity and efficiency, research to develop a practical pulsed detonation engine (PDE) has persisted since the early 1940's¹. The ability to detonate practical fuels, still remains as a technology hurdle; however, great strides have been made in the last decade²⁻⁵. Other technological hurdles include the ability to aspirate the PDE at subsonic speeds without significantly decreasing performance. Two methods to self-aspirate a PDE, an ejector pump and a turbo-charger, are investigated to determine the ability of these systems to survive

and operate in the harsh supersonic environment of the PDE. Many studies have been conducted that show an increase in performance of an ejector in a pulsing environment; however, no published experimental studies were found that describe the operation of a ejector in the supersonic exhaust flow of a PDE⁶⁻¹¹. No studies in the open literature describe the interaction of a turbine or a compressor operated in the high-temperature pulsing-supersonic flow of a PDE. In this study, both an ejector and a turbo-charger are experimentally evaluated as means to self-aspirate a PDE.

Experimental Apparatus

Two separate experiments were conducted; however, much of the experimental apparatus for the two experiments was identical. Both experiments were performed using the research PDE at the Air Force Research Labs (AFRL) at Wright-Patterson Air Force Base. The valves on a General Motors "Quad 4" automobile cylinder head were used to start and stop the

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fuel-air mixture and purge air flow into the detonation tube. The intake valves were used to fill the detonation tube with a hydrogen-air mixture and the exhaust valves were used to purge the detonation tube with air. The hydrogen and air was mixed upstream of the valves in the “intake” manifold, not in the detonation tube. The hydrogen-air mixture was ignited with a spark and a deflagration to detonation transition (DDT) process was used to achieve a detonation. Additional information concerning the AFRL research PDE is given by Schauer *et al.*⁵. The details that are specific to the ejector experiment and turbine-compressor experiment are described below.

Ejector experiment

Experiments on three ejector-detonator tube arrangements were conducted. In all the configurations, the ejector consisted of a 6" (152 mm) diameter 36" (914 mm) long pipe placed in line with the detonation tube. The detonation tube and ejector pipe overlapped for approximately 12" (305 mm). In the first experiment, the detonator tube was 2" (51 mm) in diameter and 36" (914 mm) long, and the back end of the ejector was closed except for a 2" (51 mm) diameter tube where the secondary airflow could be measured, see Fig. 1.

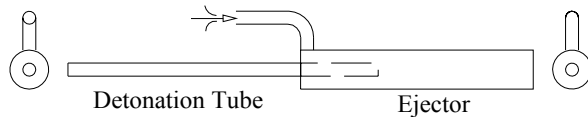


Figure 1. Schematic of 36" (914 mm) detonation tube and ejector for induced secondary flow measurement with ducted inlet

In the second experiment, the geometry was changed to increase the opening of the inlet of the ejector. The inlet of the ejector was open, except for the web that held the ejector in place, see Fig. 2. The geometry of the detonation tube in the second and third experiment was 2" (51 mm) diameter and 72" (1,829 mm) long.

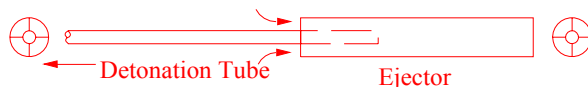


Figure 2. Schematic of 72" (1,829 mm) detonation tube and ejector with webbed ejector inlet

In the third experiment, the geometry was the same as the second experiment with the exception that a 5" diameter disk was placed at the end of the detonator tube, see Fig. 3. This disk created a half-inch annular flow path for the induced secondary flow.

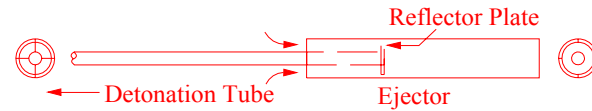


Figure 3. Schematic of 72" (1,829 mm) detonator tube and ejector with a 5" (127 mm) reflector plate

The induced airflow was measured with a “hot-wire” style velocity sensor. The output of this type of velocity sensor is not flow-direction sensitive. Flow visualization was used to determine if a secondary airflow was being induced or if exhaust products were flowing out of the intake of the ejector. Flow visualization was accomplished in two different ways for the two different styles of ejector inlets. For the ejector with the small inlet, a paper towel was wedged into the 2" (51 mm) inlet prior to starting the engine. For the webbed-ejector-inlet, a weighted string was hung at the entrance of the ejector and observed during the experiment.

Turbine-compressor experiment

In this experiment, an automotive turbo-charger was attached to the detonation tube to examine whether a compressor and turbine could be used in the harsh pulsing flow of a pulse detonation engine. Two detonation tubes were connected and fired simultaneously. The purpose of using two detonation tubes in parallel was to increase the effective valve area. A 45 deg-lateral-pipe-fitting was used to split the exhaust flow. Part of the exhaust gas flowed through the turbine and part of the exhaust gas flowed through a nozzle, see Fig 4.

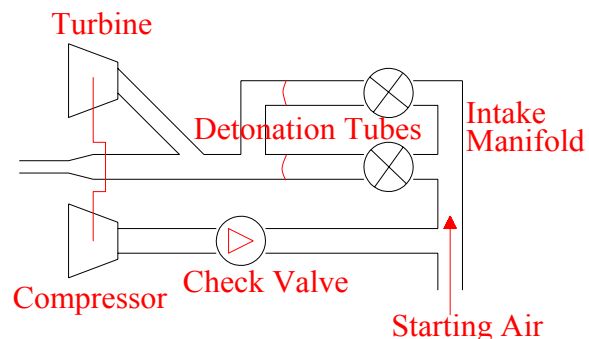


Figure 4. Schematic of turbine-compressor experiment

The inlet of the compressor was connected to a flow meter, while the exit of the compressor was connected to the inlet of the PDE. A check valve was used to prevent air from flowing backwards from the intake manifold of the PDE through the exit of the compressor, see Fig. 4. In Fig. 5, a picture of the hardware is presented.

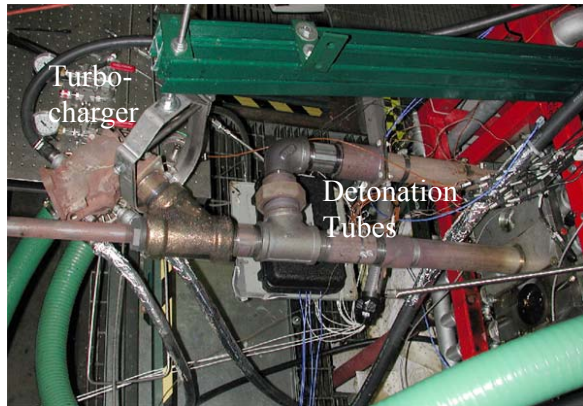


Figure 5. Photo of turbine/compressor experiment

Experimental Results and Discussion

Ejector results

The first experiments conducted on the ejector were used to determine the direction of flow at the ejector inlet. For the ducted inlet ejector, see Fig. 1, the flow direction was determined by placing a paper towel in the inlet. For some conditions, the flow at the inlet was bi-directional and at other conditions, a unidirectional secondary flow was induced. In Fig. 6 several images are presented of the successful induction of a secondary flow. In Fig. 6a, the ejector is shown with a paper towel wedged in the ducted inlet and a streamer extending several feet out of the inlet prior to the experiment. In Fig. 6b, the steamer is shown being pulled into the inlet of the ejector after the PDE began firing. In Fig. 6c, a large portion of the paper towel can be seen to have exited the ejector and when the exhaust gas from the next detonation exits the ejector, a diamond shaped expansion pattern can be seen as the paper towel had collected in the high-density region of the shock waves. Finally, in Fig. 6d, it is apparent that the entire steamer has been ingested and expelled by the ejector.



(a)



(b)



(c)



(d)

Figure 6. Flow visualization of secondary-air entrainment: (a) prior to firing the PDE, (b) the paper towel was steadily ingested, (c) diamond shock pattern visualized in exhaust, and (d) the entire paper towel and streamer was expelled out the end of the ejector

Not all conditions induced a secondary flow. In some experiments the paper towel would oscillate in the inlet of the ducted-inlet-ejector before being expelled out of the ejector inlet. The equivalence ratio and fill fraction (ff) were found to affect the induced flow. In Table 1, the conditions under which a secondary airflow was induced are given. At high fill fractions and high equivalence ratios, the flow at the inlet of the ejector was oscillatory, repeatedly flowing in and then out. The oscillatory flow was considered a failure.

Table 1. Conditions where a secondary flow was induced in the ejector and 36" detonation tube

	ff=1.0	ff=0.75	ff=0.5	ff=0.25
$\phi=1.0$	Failure	Failure	Success	Success
$\phi=0.75$	Failure	Failure	Success	Success
$\phi=0.5$	Success	Success	Success	Success

In Figs. 7 and 8 are plotted the ejector wall pressure at four different locations along the ejector. Comparing the pressure traces at the inlet and 12" (305 mm) downstream of the ejector inlet, it was apparent that in the case of failure to induce a secondary airflow, a shock wave propagated upstream in the ejector. In Fig. 7, the pressure at the

inlet of the ejector was unaffected by the shock wave propagating from the end of the detonation tube.

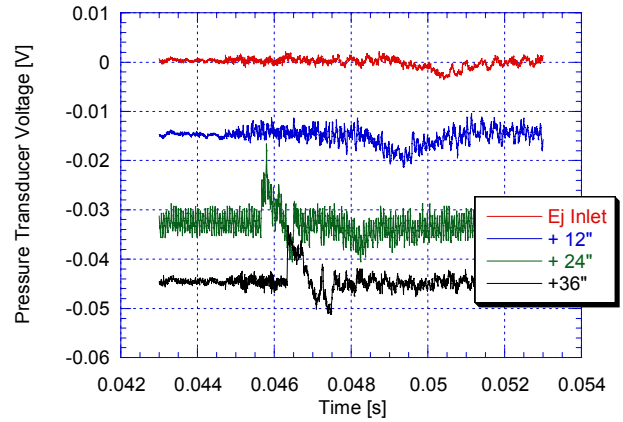


Figure 7. Ejector wall pressure: successful entrainment of secondary-air flow

The shock wave that propagated from the end of the detonation tube was evident in the pressure on the ejector wall at 24" and 36" (610 and 914 mm) from the ejector inlet. In Fig. 8, it was evident that the shock wave leaving the detonation tube traveled upstream in the ejector. Eventually the pressure at the ejector inlet decreases below the baseline. The shock wave followed by the suction at the inlet caused the oscillatory flow seen at the ejector inlet during some of the flow visualization experiments.

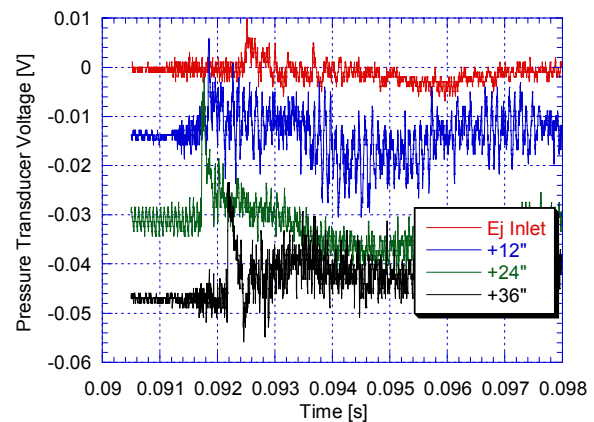


Figure 8. Ejector wall pressure: failure to entrain secondary-air flow

The induced airflow was measured as a function of fill fraction at two frequencies and an equivalence ratio of unity and presented in Fig. 9. Note that for fill fractions 0.75 and above, the flow at the injector inlet was oscillatory. At 20 Hz and a fill fraction of 0.5 the induced flow was approximately 3.4 times greater than the

primary airflow required by the PDE. At 40 Hz, and a fill fraction of 0.5 the induced airflow was approximately 3 times the primary airflow. For three of the four conditions tested at 40 Hz, the doubling of the frequency from 20 to 40 Hz resulted in an increase in the induced airflow of greater than 70%. For the case of a fill fraction of 0.75, the airflow increased by 50%.

The failure to induce a secondary flow at high fill fractions and high equivalence ratios was attributed to fuel burning or detonating at the exit of the detonation tube or inside the ejector. It was postulated that when the intake valve first opens, there was mixing between the fuel-air charge and the purge air. The mixing would decrease the equivalence ratio in this part of the charge and increase the volume of the air mixed with the fuel; thereby, over-filling the detonation tube. At low fill fractions this diluted charge was still in the detonation tube and a secondary flow was induced. At high fill fractions and low equivalence ratios, the equivalence ratio of the mixture at the exit or just outside the detonation tube may have been too low to detonate.

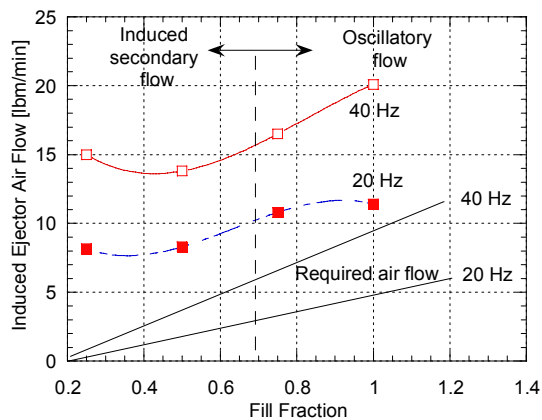


Figure 9. Induced secondary air flow, $\phi=1.0$

In the last experiment conducted with the ejector a round disk was placed at the exit of the detonation tube and inside of the ejector, see Fig. 3. The purpose of the disk was to reflect the shock wave produced by the detonation at the exit of the detonation tube toward the exit of the ejector. In Table 2, flow visualization was used to determine if the ejector was inducing a secondary flow. With the reflector plate installed, the conditions of 0.75 fill fraction and an equivalence ratio of 0.75 was successful in inducing a secondary flow were previously, this condition created an oscillatory flow in the inlet of the ejector, cf. Table 1.

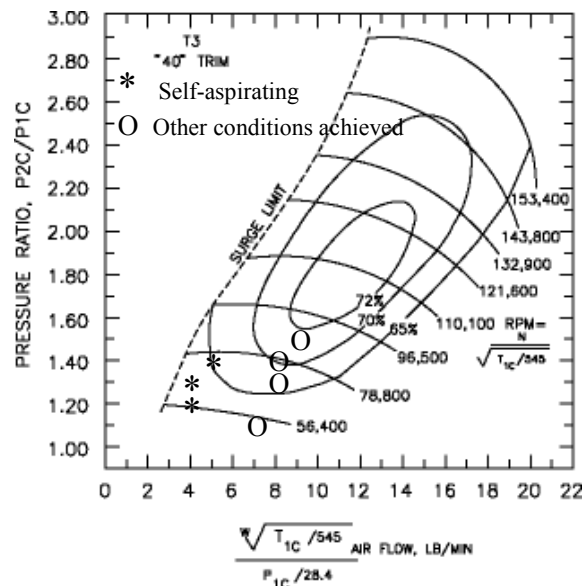
Table 2. Conditions where a secondary flow was induced in the ejector on a 72" (1,829 mm) detonation tube with reflector plate

	ff=1.0	ff=0.75	ff=0.5	Ff=0.25
$\phi = 1.0$	Failure	Failure	Success	Success
$\phi = 0.75$	Failure	Success	Success	Success
$\phi = 0.5$	Success	Success	Success	Success

Identical experiments were conducted on the 72" (1,829 mm) detonation tube and ejector without the reflector plate, see Fig. 2, and the results were identical to those shown in Table 1.

Turbine/compressor results

Several experiments were conducted with the turbo-charger connected to the detonation tube of the PDE. In Fig. 10, the conditions achieved with the compressor of the turbo-charger are plotted on a compressor map. The compressor operated at rotational speeds from 55K to 80K rpm. In most of the experiments, the PDE was run for 30 to 60 seconds; however, a 25-minute self-aspiration run was conducted.



seconds of operation, the facility air flowing through the intake manifold was turned off, and the compressor on the turbo-charger was used to supply air. Purge air was still supplied by the facility compressors.

In Fig. 11, the airflow and thrust are plotted for this 25-minute self-aspirated run. The average measured airflow through the compressor driven by the turbine was very similar to the airflow rate used to start the engine. The fluctuations in the measured airflow rate through the turbine-driven-compressor were attributed to the oscillating check valve. The thrust of the PDE was reduced by approximately 20% while the PDE was self-aspirated via the turbo-charger

The temperature of the detonation tubes and turbine housing during this extended run were recorded and are presented in Fig. 12. The turbine housing temperature was significantly higher than the detonation tube wall temperature. The steady-state temperature of the detonation tube and turbine housing was reached in less than 500 seconds. A picture of the turbine after experiencing 35,000+ detonation cycles is presented in Fig 13. The turbine showed no signs of discoloration or pitting.

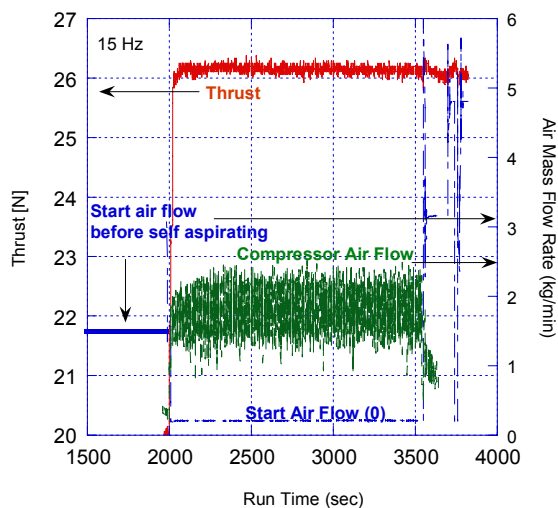


Figure 11. Airflow and thrust for a 25 minute self-aspirated run

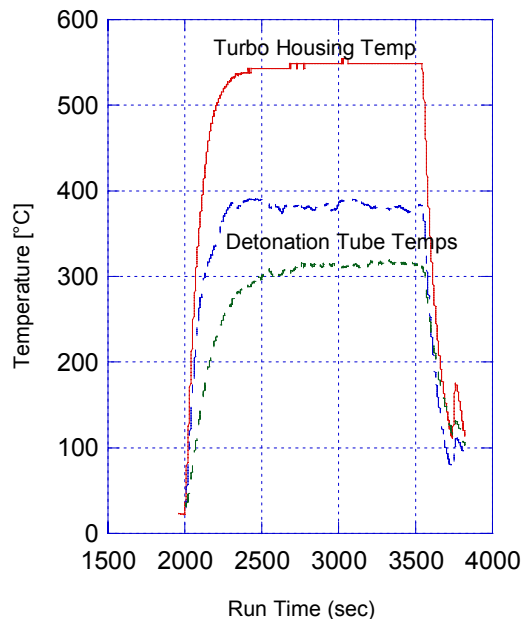


Figure 12. Detonation tube and turbine housing temperatures during the 25 minute self-aspirated run

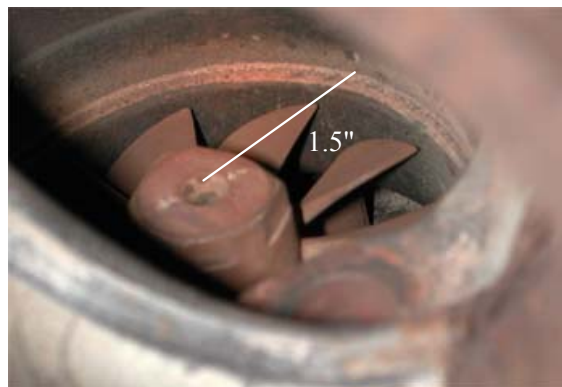


Figure 13. Turbine blades after over 35,000 detonation cycles

Summary and Conclusions

From these experiments, it has been shown that a PDE can be self-aspirated. The secondary flow can be induced in the supersonic-pulsing environment of a PDE. The fill fraction and equivalence ratio were found to be the primary variables affecting the success or failure of this ejector. The secondary induced flow was over 3 times the primary flow indicating that self-aspiration with an ejector pump was possible. Additional experiments

optimizing the ejector geometry and using the ejector to self-aspirate the PDE are planned

In the turbo-charger experiment, it was shown that a turbine and compressor survived and operated in the pulsing-shock-environment of a PDE. A 25-minute self-aspirated run was accomplished. Additional experiments with axial flow turbines and compressors are planned as well as experiments that use the turbine to increase the pressure in the detonation tube prior to detonation.

Acknowledgments

Appreciation is expressed to the technicians and facility personnel who made this work possible. We also would like to recognize the technical leadership of Dr. Mel Roquemore and Dr. Robert Hancock (AFRL/PRTS).

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Table 1 Conditions where a secondary flow was induced in the ejector and 36" detonation tube

	ff=1.0	ff=0.75	ff=0.5	ff=0.25
$\phi = 1.0$	Failure	Failure	Success	Success
$\phi = 0.75$	Failure	Failure	Success	Success
$\phi = 0.5$	Success	Success	Success	Success

Table 2 Conditions where a secondary flow was induced in the ejector on a 72" detonation tube with reflector plate

	ff=1.0	ff=0.75	ff=0.5	Ff=0.25
$\phi = 1.0$	Failure	Failure	Success	Success
$\phi = 0.75$	Failure	Success	Success	Success
$\phi = 0.5$	Success	Success	Success	Success

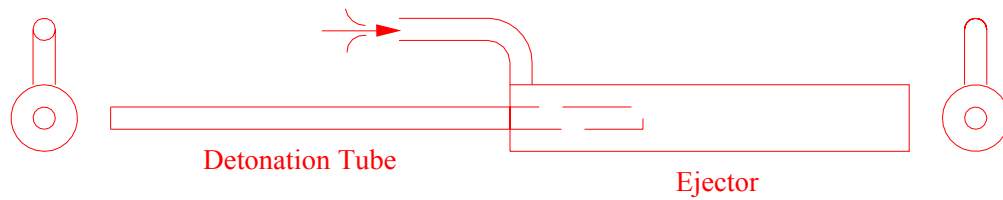


Figure 1 Schematic of 36" detonation tube and ejector for induced secondary flow measurement with ducted inlet

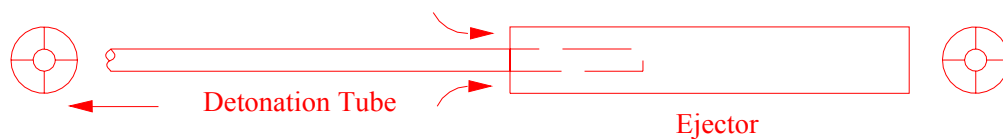


Figure 2 Schematic of 72" detonation tube and ejector with webbed ejector inlet

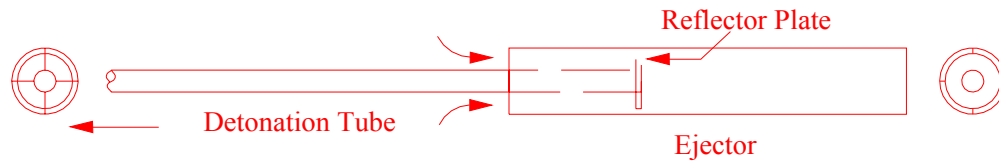


Figure 3 Schematic of 72" detonator tube and ejector with a 5" reflector plate

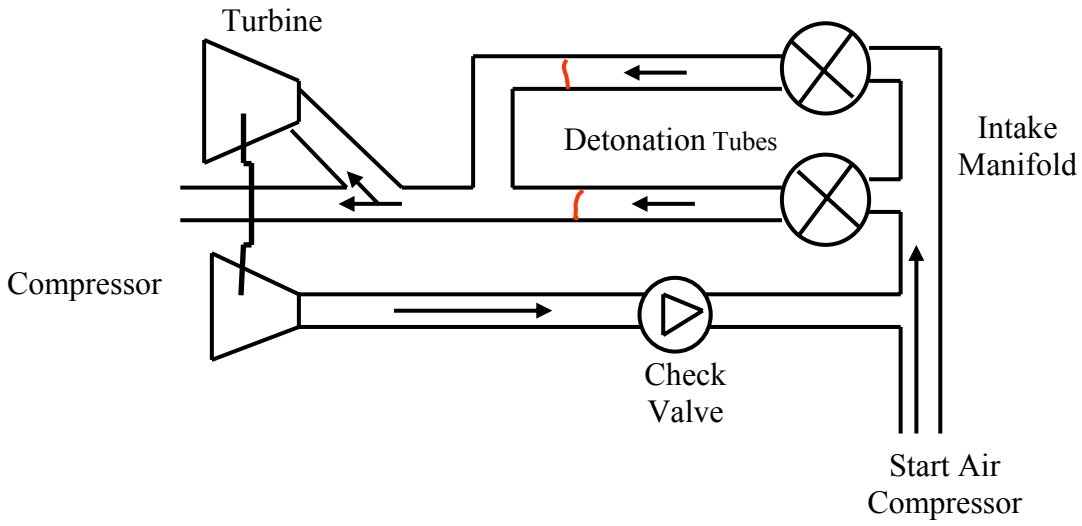


Figure 4 Schematic of turbine/compressor experiment

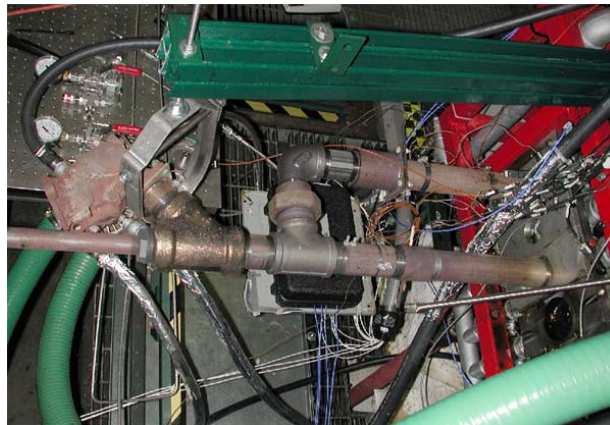


Figure 5 Photo of turbine/compressor experiment



(a)



(b)



(c)



(d)

Figure 6 Flow visualization of secondary-air entrainment

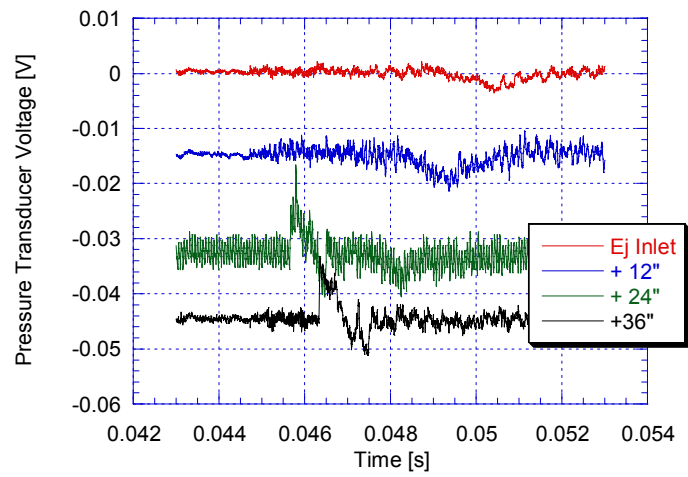


Figure 7 Ejector wall pressure: successful entrainment of secondary-air flow

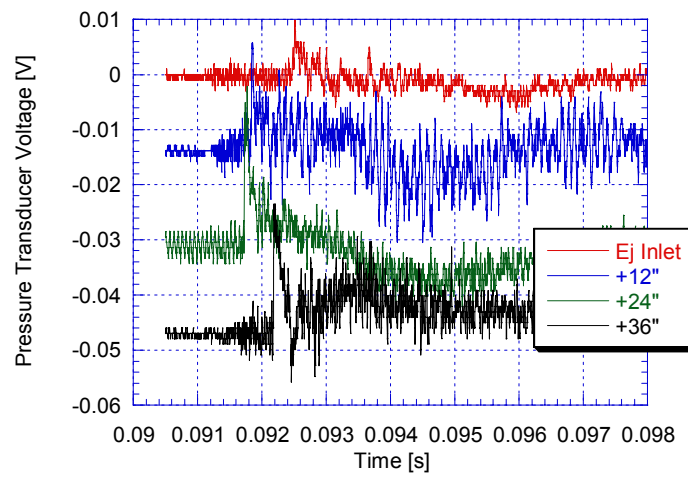


Figure 8 Ejector wall pressure: failure to entrain secondary-air flow

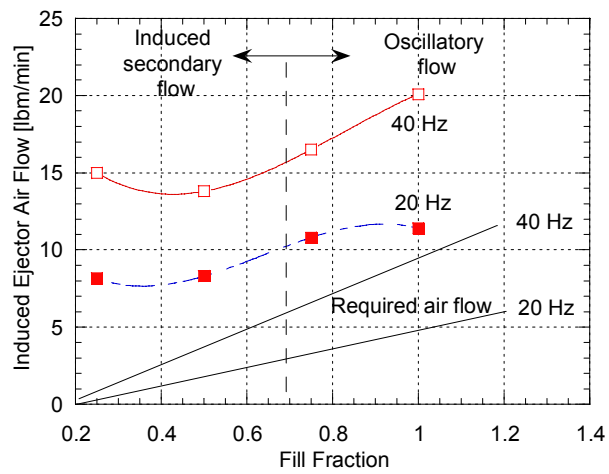


Figure 9 Induced secondary air flow, $\phi=1.0$

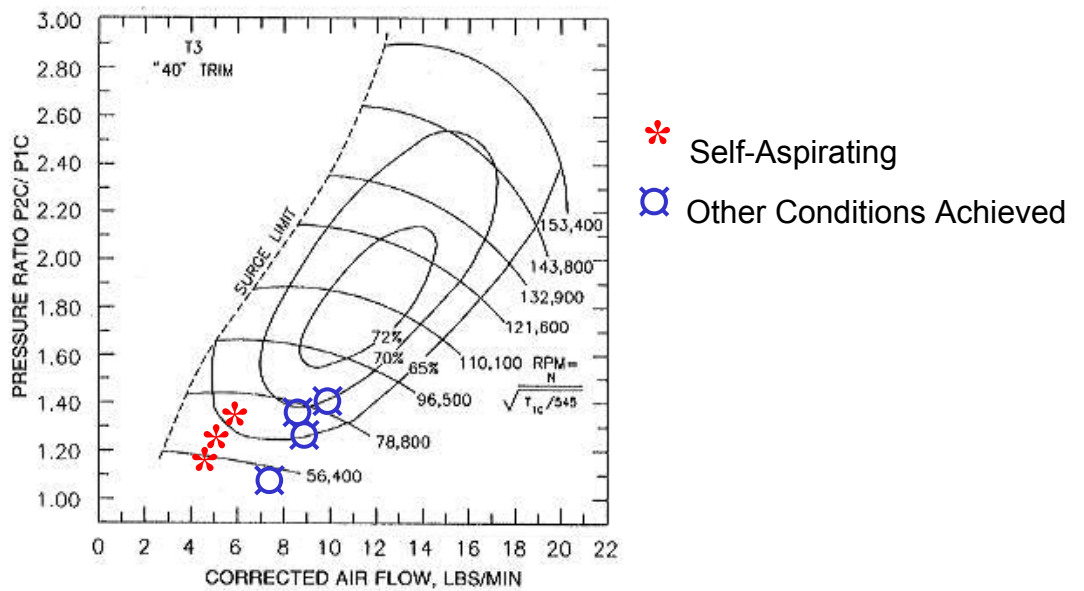


Figure 10 Compressor conditions achieved plotted on the compressor map (modified and reprinted from website of Turbonetics Inc.)

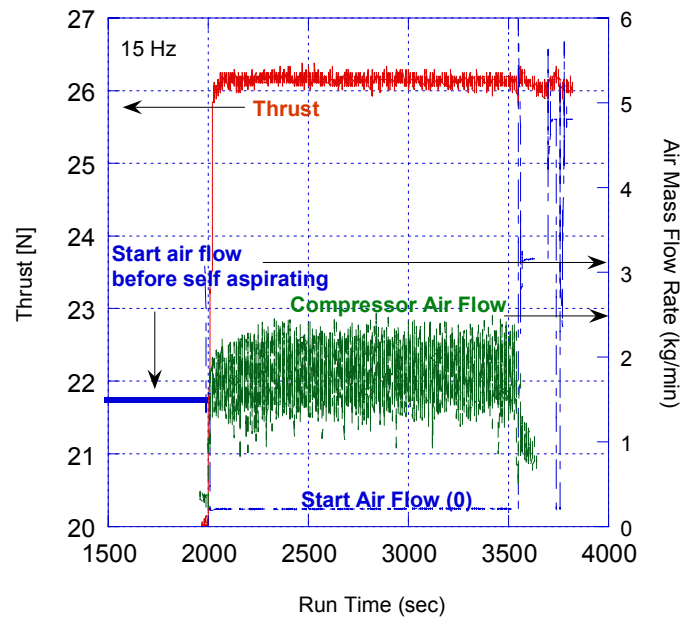


Figure 11 Airflow and thrust for a 25 minute self-aspirated run

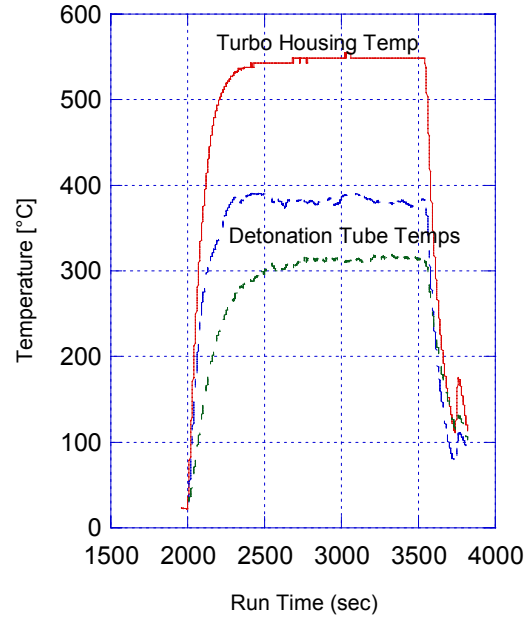


Figure 12 Detonation tube and turbine housing temperatures during the 25 minute self-aspirated run



Figure 13 Turbine blades after over 30,000 detonation cycles