AIAA 2003-0891

INTERACTION OF A PULSED DETONATION ENGINE WITH A TURBINE

Fred Schauer, Royce Bradley[*], and John Hoke[*]
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson AFB, OH 45433
[*]Innovative Scientific Solutions, Inc.
Dayton, OH 45440

41st AIAA Aerospace Sciences Meeting & Exhibit
6-9 January 2003
Reno, NV

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Interaction of a Pulsed Detonation Engine with a Turbine**	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	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

AIAA 2003-0891

INTERACTION OF A PULSED DETONATION ENGINE WITH A TURBINE

Fred Schauer*

Air Force Research Laboratory, Propulsion Directorate

Wright-Patterson AFB, OH 45433

Royce Bradley and John Hoke

Innovative Scientific Solutions, Inc.

Dayton, OH 45440

Abstract

An evaluation of a pulsed detonation engine (PDE) blowing down through a turbine is presented. In previous experiments, a coupled PDE-turbocharger had demonstrated shaft power extraction and self aspiration. (**AIAA 2002-0615**). This more recent work adds additional instrumentation, configurations, and operating conditions in order to further study the detonation driven turbine. A PDE detonator tube exhaust drives a centrifugal turbine. A connected centrifugal compressor with regulated outlet pressure and measured inlet flow enables the determination of the achieved operating conditions. The turbine was spun to over 130,000 rpm and was studied at virtually all significant conditions on the turbine operating map, including such conditions as high compressor flow rates and outlet pressures. In addition, significant back-pressurization of the detonation tube was demonstrated under some operating conditions. Selected operating conditions, are compared to theoretical calculations, demonstrating high losses through the expansion throught the turbine. The turbine survived all testing despite detonation in the inlet. The turbine significantly attenuated the strength of detonation driven shocks in the exhaust nozzle.

Introduction

Because of the simplicity and efficiency, research to develop a practical pulsed detonation engine (PDE) has persisted since the early 1940's[1]. The ability to detonate practical fuels, still remains as a technology hurdle; however, great strides have been made in the last decade[2-5]. Other technological hurdles include the ability to aspirate the PDE at subsonic speeds without significantly decreasing performance and to extract auxiliary power for running accessories and exhange components. A turbine is evaluated to examine its performance when driven by detonation exhaust and to determine the ability of rotating machinery to survive and operate in the harsh supersonic environment of the PDE

Previously[6], an automotive turbo-charger (Garrett T3) was attached to a 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 1.

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. The check valve was used to prevent air from flowing backwards from the intake manifold of the PDE through the exit of the compressor when self-aspirating.

The experimental configuration demonstrated the feasibility of utilizing a turbine in a pulsed detonation

---

[*] Author to whom correspondence should be addressed: frederick.schauer@wpafb.af.mil, (937) 255-6462 Fax: (937) 656-4570

flow path. Further instrumentation and configurations were explored in order to quantify the turbine performance.

Experimental Setup

AFRL's research PDE at Wright-Patterson AFB was used to control the detonations. Further details on this engine, control system, and instrumentation are described in detail elsewhere[5]. A single 36" long, 2" inside diameter detonation tube was connected directly to the turbine inlet, forming an effective detonation tube of 38" length between the PDE valves and the turbine as shown in Figure 1.

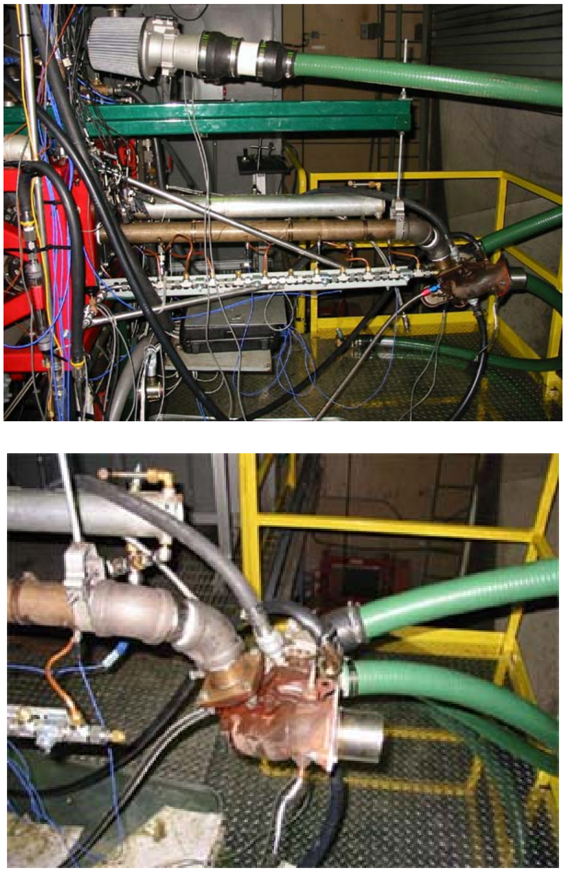

Figure 1. Photo of turbine/compressor experiment with research PDE and detonator tube connected directly to turbine. Lower photo shows detail of detonator tube entering turbine and mount for nozzle extensions (nozzle not installed). Green hoses are plumbing for compressor mass flow sensor on inlet (just down-stream of intake filter in top of upper photo) and connection of pressure regulator on compressor outlet.

Dynamic pressure transducers were located down the length of the detonation tube and beyond the turbine as indicated in Table 1. In a addition, a static pressure transducer was located near the head (P7 or trace 7) in the hopes of accurately measuring the initial pressure.

Location (in)	Label (Description)
-0.857	P1 (Detonator Tube Head)
3.75	P7 (Static Pressure near Head)
18.75	P2 (Detonator Tube)
24.69	P3 (Detonator Tube)
31.06	P4 (Detonator Tube)
37.06	P5 (Turbine Inlet)
38.75	Turbine Location
61.75	P7 (Turbine Exit)

Table 1. Location of pressure transducers.

The compressor outlet was not connected to the PDE inlet, but was dumped via a bleed valve in order to regulate compressor pressure ratio. The compressor flow was measured upstream of the compressor with a mass air flow sensor[6].

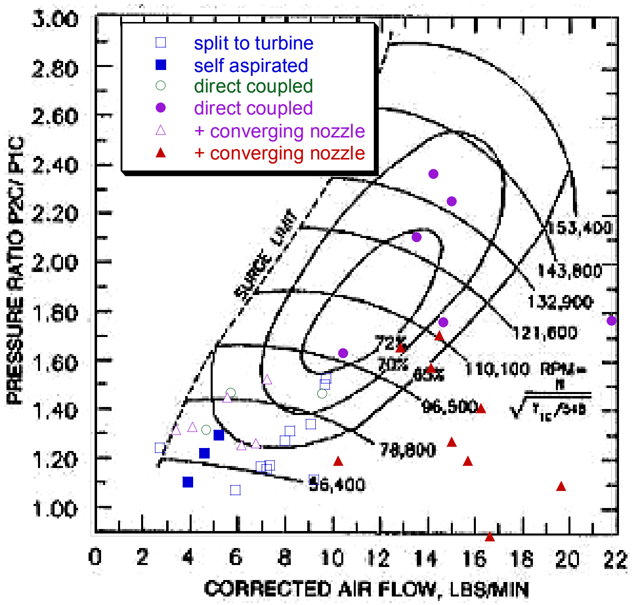

Figure 2. Compressor operating map with points achieved during testing. Filled triangles are points presented in detail.

As indicated in the compressor operating map shown in Figure 2, a wide variety of turbine/compressor operating conditions were obtained, including high flow rates, high compressor pressure ratios, and up to 135,000 rpm. The turbine relief valve was disabled so that the detonating flow was forced through the turbine. The points denoted by filled triangles will be analyzed in further detail. The remaining points include, the bypassed turbine configuration and self-aspiration discussed elsewhere6, and additional direct connect tests which included various extensions and nozzles on the turbine exit. A preponderance of data drives the need to limit the data presented to the 9 points indicated in Table 2. All points were collected with stoichiometric hydrogen/air mixture.

Run	freq	Tube Fill	Initial Pressure	Thrust	Compressor Flow	Compressor Pressure Ratio
(with Turbine)			~ psig	lbf	lb/min	
1	20	1.0	9	3.72	16.86	1.05
2	20	2.0	24	8.81	15.94	1.29
3	30	1.0	8	6.44	10.45	1.29
4	30	2.0	11	12.53	13.08	1.73
6	40	1.0	14	8.36	19.87	1.19
7	40	1.0	13	8.94	15.24	1.36
8	40	1.5	16	13.92	16.49	1.49
9	40	1.5	22	13.98	14.37	1.65
10 (no nozzle)	40	1.5	12	12.05	14.72	1.77

Table 2. Operating conditions anaylyzed in this paper.

The indicated tube fill fraction assumes the detonator tube is completely filled to the turbine with detonable mixture at STP and does not take into account initial pressure variations. Thus, the tube fill fraction is an indcator of SCFM, and must be corrected to reflect ACFM and actual fill fraction accurately. The initial pressure as approximated in Table 2 may be used to find the actual fill fraction. However, the fill process is highly dynamic, and the initial tube pressure for each cycle is a function of time and location. In addition, previous measurements have indicated reactants do not flow down the tube smoothly without significant mixing with purge and/or exhaust products[7].

Except for run 10, the presented data was obtained with a 12" extension on the turbine outlet with a converging nozzle of 1.5" inside diameter with a short aspect ratio (consisting of a bell-mouthed pipe reducer screwed into a 12" nipple which was welded on a flange abutting the turbine exit). Run 10 is identical to the other geometries except the converging nozzle was removed.

Experimental Results

The data from each of the 10 runs discussed above, was reduced using the methods described elsewhere[8]. Results include pressure histories, wavespeeds, thrust, and compressor power output.

Shown in figure 3 are pressure traces from run 10. The traces are offset by 300psig for each location in order to clarify the detonation dynamics. Each of the other runs indicated similar results; generally: deflagration transistions to detonation befroe transducer location P2, and the resulting Chapman-Jouget detonation propagates to or near the turbine inlet. A backwards-propagating shock is observed as the relection of the detonation off the turbine. Only weak pressure rise is observed downstream of the turbine (P6).

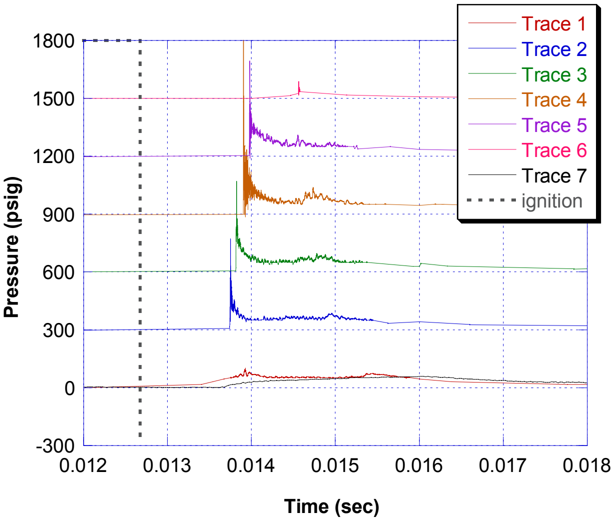

Figure 3. Pressure traces for run 10, showing detonation, schok reflection from turbine, and blow down. Note weakened shock beyond turbine exit (trace 7).

Wavespeeds are plotted versus location in Figure 4 for both runs 1 and 9 (runs 8, 9, and 10 were similar). From Table 2, it is readily apparent that the initial pressure during run 1 was higher than STP, resulting in the indicated fill fraction of 1.0 producing an under-filled condition. This may be the cause of the sub-Chapman-Jouget wavespeed shown near the turbine exit. Wavespeeds can be noted to fall off rapidly beyond the turbine location which is denoted via the dashed line and with the 'TC' label.

A closer look at head pressure traces reveals differences between the static (P7) and dynamic (P1) transducer measurements in Figure 5. The differences here are a result of the AC nature of the dynamic transducer, and the slow response time (kHz) of the static transducer. The static pressure transducer lags but maintains a quantitative voltage throughout the cycle, and perhaps measures some low frequency components that the dynamic measurement does not. The minimal difference in location (~ 4") should not be a cause of trace differences at the plotted time scales. A complete PDE cycle is shown, with the sharp rise in pressure indicating arrival of the retonation wave, followed by detonation blow down, and the second and third smaller humps revealing the purge and fill cycles respectively. The fill cycle continues on the next PDE cycle, as shown when it is followed back to the beginning of the plotted cycle.

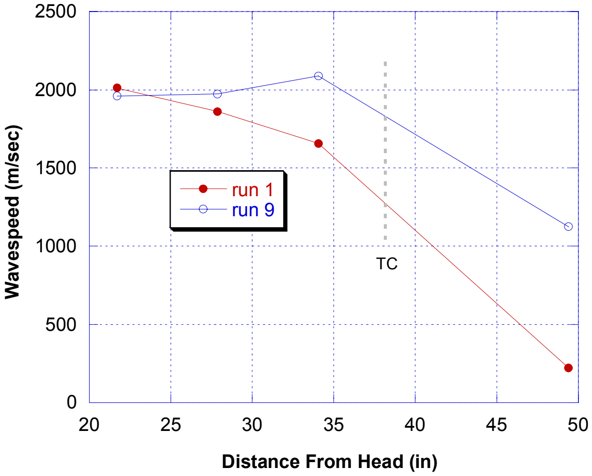

Figure 4. Wavespeed versus location for two operating conditions. Location of turbine is indicated by dashed line denoted 'TC'.

From the static transducer results, it is evident that the initial pressure before detonation varies from 5 to 18 psig in the 5 msec before detonation initiation. This is a source of uncertainty in a meaningful ACFM for calculating the real fill fraction of table 2. From spark to detonation initiation is on the order of 2 msec, making it difficult to know the actual fill pressure and mixture levels. Consequently, the fill fraction is calculated for SCFM as discussed above. Little effect upon the detonation was noted as a result of increased initial pressures other than perhaps a slight increase in pressures and wave speeds.

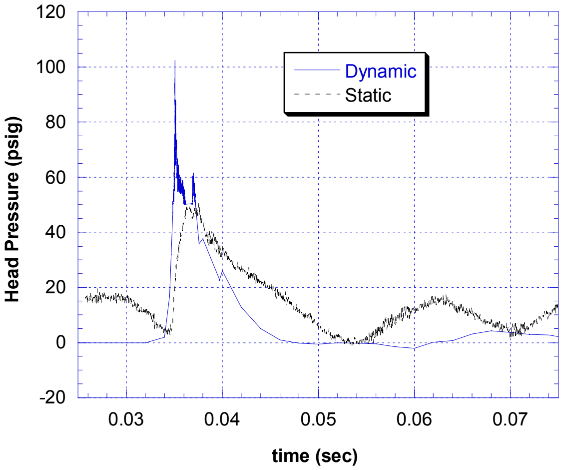

Figure 5. Dynamic and static head pressure transducers versus time.

One would expect that detonation blow times would be prolonged with the introduction of a turbine and nozzle to the detonator tube exit. The dramatic rise in blow down time is observed in Figure 6 where the detonation driven turbine blow down time is comparted with the blow down times from several other geometries. The simple PDE is similar to the geometry that would be present if the turbine and aft were removed. The PDE with straight extension (here a 2' extension was used to provide a similar overall length to the PDE-turbine geometry) can be compared to the effect of adding additional length post-turbine, but without the flow interactions of the turbine.

The turbine impedes the blow down in a manner similar to a contracting nozzle which tripled the blow down time for the 2:1 contraction presented here. However the detonation blow-down time of the PDE driven turbine extends into the fill cycle (after 17 msec for the 20 Hz detonations shown here), resulting in back pressurization. The back pressurization is observable via the higher than ambient initial pressures of Table 2. Note the differences in back- pressurization between runs 9 and 10 which have different exit areas only. The exit areas are significantly larger than the effective turbine flow area so it the sensitivity to exit area is suprising.

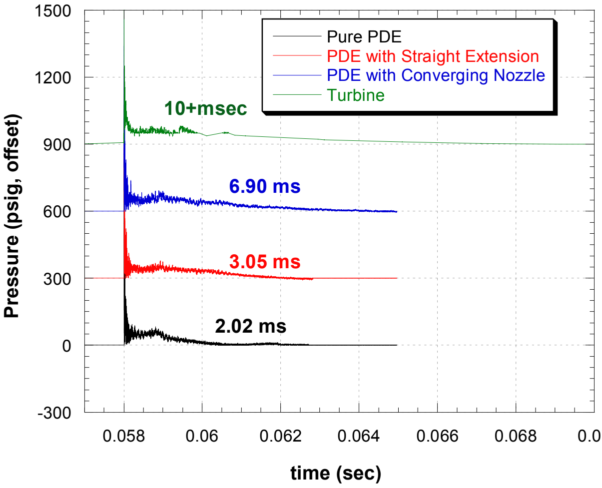

Figure 6. Detonation pressure blow down times for PDE, PDE with straight extension, PDE with 2:1 converging nozzle, and PDE exhausting through turbine.

In addition to the head pressures, the exit pressures provide some indication of the interaction of the turbine with the detonation process. Instead of the usual ~30 atm shock moving down the exit region, the turbine attenuates the shock. Peak turbine exit pressures and wavespeeds are in Table 3 for each run condition, as well as compared for extreme cases in figure 7 for runs 1 and 9. Again run 1, with a lower effective fill fraction due to back-pressurization, has a weaker interaction with the turbine and a resultant weaker exit pressure wave. Even the stronger pressure waves of run 9 have significantly degraded from Chapman-Jouget conditions in going through the turbine.

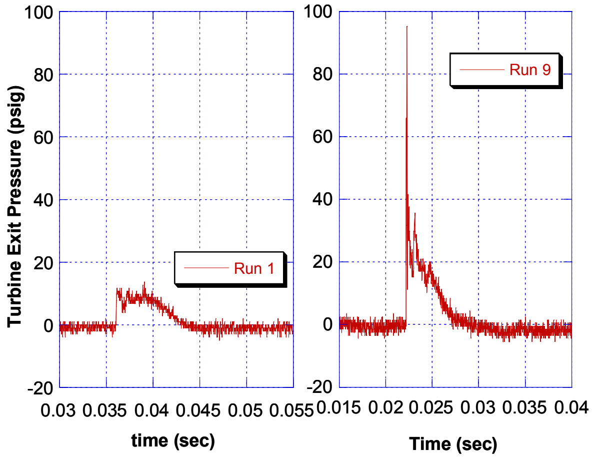

Figure 7. Turbine exit pressure profiles for two run conditions.

Performance Analysis

Performance values contained in Table 3, consisted of straightforward analysis of the PDE thrust[9,10] along with classical analysis of the steady compressor (Van Wylan and Sonnttag[11] among others). Heating value is from Povinelli and Yungsters' recent work which assumes recombination reactions[10]. The 'no turbine' PDE data point included at the bottom of Table 2 is from experimental data from the same engine with a conventional detonation tube which has been validated against various models [5,10].

The 'ideal' PDE performance assumes perfect isentropic expansion of the Chapman-Jouget conditions to the thrust wall and then to ambient conditions. Such an engine would require a loss-less 'rubber nozzle' and therefore no actual performance parameters are included for this idealized case.

Despite the same theoretical expansion of the detonation pressure through the turbine and for producing pure thrust, the performance is quite different. Even accounting for the 60-75% efficiency of the turbine/compressor in the total work, the overall efficiency of the detonation blowdown drops by a factor of ~ 4 when driving a turbine as opposed to making pure thrust (for all cases compared to the 'no turbine' PDE).

Run	freq	Tube Fill	ST	ISP	Compressor Work	Total Work	Combustion Heat Release	Thermal Efficiency
(with Turbine)			lb/lb/sec	sec	kW	kW	kW	%
1	20	1.0	44	1526	0.5	4.5	120.4	3.7%
2	20	2.0	52	1807	2.7	14.3	240.8	5.9%
3	30	1.0	51	1761	1.8	10.0	180.6	5.5%
4	30	2.0	50	1713	5.0	21.2	361.3	5.9%
6	40	1.0	50	1715	2.3	12.7	240.8	5.3%
7	40	1.0	53	1834	3.2	15.3	240.8	6.4%
8	40	1.5	55	1903	4.5	23.8	361.3	6.6%
9	40	1.5	55	1911	5.0	24.6	361.3	6.8%
10 (no nozzle)	40	1.5	48	1648	5.9	21.4	361.3	5.9%
No Turbine								
PDE	40	1.0	119	4104		53.7	240.8	22.3%
Ideal								53.5%

Table 3. Performance results for PDE driving turbine, PDE with no turbine, and ideal pulsed detonation cycle.

Although the detonation driven turbine performance was poor, there is cause for optimism. Turbines such as the Garrett T3 were never designed to operate in such an environment. Fully developed detonations were propagating directly into the turbine inlet and yet the turbine still functioned despite 50,000+ detonations. No visible pitting or discoloration is visible as shown in Figure 8.

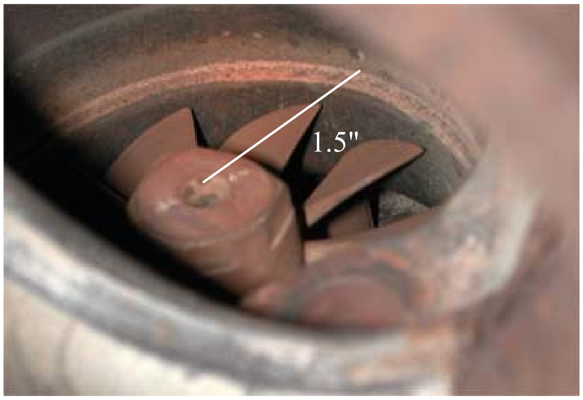

Figure 8. Turbine after 50,000+ detonations.

Summary and Conclusions

A Garret T3 turbine was driven by a pulsed detonation engine in order to simultaneously extract shaft power and produce thrust. The turbine was spun to over 130,000 rpm and was studied at virtually all significant conditions on the turbine operating map, including such conditions as high compressor flow rates and outlet pressures. In addition, significant back-pressurization of the detonation tube was demonstrated under some operating conditions. Selected operating conditions, are compared to theoretical calculations, demonstrating high losses through the turbine stage expansion. The turbine survived all detonation driven operation despite detonation in the inlet. The turbine significantly attenuated the strength of detonation driven shocks in the exhaust nozzle.

Acknowledgments

Appreciation is expressed to the technicians and facility personnel who made this work possible, particularly Jeff Stutrud. We also would like to recognize the technical leadership of Dr. Mel Roquemore and Dr. Robert Hancock (AFRL/PRTS). This work was performed under funding from AFOSR and AFRL.

References

1. Proctor, P., "Pulse Detonation Technologies Advance". *Aviation Week and Space Technology*: p. 48(1998).

2. Brophy, C.M., D. Netzer, and D. Forster. "Detonation Studies of JP-10 with Oxygen and Air for Pulse Detonation Engine Development". in *34th Joint Propulsion Conference*. Cleveland: AIAA (1998).

3. Eckett, C.A., J.J. Quirk, and J. Shepherd, *The Role in Direct Initiation of Gaseous Detonations*. 2000.

4. Santoro, R.J. "PDE- Progress and Challenge". in *The 2001 Technical Meeting of the Eastern States Section of the Combustion Institute*. Hilton Head, SC (2001).

5. Schauer, F., J. Stutrud, and R. Bradley. "Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications". in *39th AIAA Aerospace Sciences Meeting and Exhibit*. Reno, NV (2001).

6. J. Hoke, R. Bradley, J. Stutrud, and F. Schauer, "Integration of a pulsed detonation engine with an ejector pump and with a turbo-charger as methods to self-aspirate," **AIAA 2002-0615**, Reno (2002).

7. Brown, M.S., "Emission and absorption based sensors for the pulsed detonation engine," *Turbine Engine Technology Symposium*, Dayton Ohio (2002)

8. Parker, J. and Schauer, F., "Data analysis and compression algorithms for megabyte-data PDE experiments," **AIAA 2002-892**, Reno (2002).

9. Dyer, R.S., and Kaemming, T.A., "The thermodynamic basis of pulsed detonation engine thrust production," **AIAA 2002-4072**, Indianapolis (2002).

10. Povinelli, L.A., and Yungster, S., "Thermodynamic cycle and CFD analysis for hydrogen fueled air-breathing pulse detonation engines," **AIAA 2002-3629**, Indianapolis (2002).

11. Van Wylen, G. and Sonnttag, R., *Fundamentals of Classical Thermodynamics*, John Wiley and Sons, New York (1985).