Chinese Journal of Aeronautics, (2013),**26**(6): 1353–1359

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Experimental investigations on the power extraction of a turbine driven by a pulse detonation combustor

Li Xiaofeng, Zheng Longxi *, Qiu Hua, Chen Jingbin

School of Power and Energy, Northwestern Polytechnical University, Xi'an 710072, China

Received 12 December 2012; revised 25 March 2013; accepted 17 June 2013
Available online 9 August 2013

KEYWORDS

Combustor;
Experiment;
Pulse detonation;
Turbine;
Turbocharger

Abstract In order to grasp the interaction mechanism between the pulse detonation combustor (PDC) and the turbine, the experimental work in this paper investigates the key factors on the power extraction of a turbocharger turbine driven by a PDC. A PDC consisting of an unvalved tube is integrated with a turbocharger turbine which has a nominal mass flow rate of 0.6 kg/s and 50000 r/min. The PDC–turbine hybrid engine is operated on gasoline-air mixtures and runs for 6^+ min to achieve a thermal steady state, and then the engine performance is evaluated under different operating conditions. Results show that the momentum difference per unit area between the turbine inlet and outlet plays an important role in the power extraction, while the pressure peak of the detonation has little effect. The equivalence ratio of fuel and air mixture and the transition structure between PDC and turbine are also important to the power extraction of the turbine. The present work is promising as it suggests that the performance benefit of a PDC–turbine hybrid engine can be realized by increasing the momentum difference per unit area through the optimal design of transition section between the PDC and turbine.

1. Introduction

Pulse detonation engines (PDEs) have drawn great attention because of their potential for increased specific impulse when compared with ramjets.[1,2] Furthermore, notional thermodynamic cycles show greater thermodynamic efficiency than Humphrey (constant volume) and Brayton (constant pressure) cycles as a result of the pressure-rise associated with a detonation,[3–5] which is a shock-induced combustion wave. The incident shock wave and trailing combustion zone are coupled such that the temperature rise across the shock initiates the combustion whose subsequent heat release provides energy to sustain the shock.[6] PDEs have been considered for potential applications across the flight envelope spanning subsonic, supersonic and hypersonic flight due to their superiority.[7,8]

Many of the proposed propulsion applications rely directly on the impulse thrust of the detonation in a simple pure tube PDE configuration where the detonation exhausts directly into the ambient atmosphere.[9–16] The most far-reaching application would be to merge the strength of current gas turbines with pulse detonation combustor (PDC) in a hybrid propulsion system, where the standard steady-flow deflagration combustor is replaced with multiple PDCs. Because the PDE system is a

---

* Corresponding author. Tel.: +86 29 88492414.
E-mail addresses: wilflxf@aliyun.com (X. Li), zhenglx@nwpu.edu.cn (L. Zheng).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

1000-9361 © 2013 Production and hosting by Elsevier Ltd. on behalf of CSAA & BUAA. Open access under CC BY-NC-ND license.
http://dx.doi.org/10.1016/j.cja.2013.07.015

cycle consisting of fill, detonation, blow-down, purge, and refill, the turbine experiences a wide range of inlet conditions including a very strong pressure pulse, a period of relatively high temperature, and a phase of low temperature and pressure corresponding to purge and refill. The interaction between a PDE system and a turbine is considerably complex. While there is plentiful experience in ensuring the turbomachinery operating very efficiently under steady sate conditions, there is little experience-base with regards to the operation of a turbine with unsteady inlet flow conditions in addition to strong wave impingement on the stator and rotor blades of the turbine.

Recently, there have been a large number of researchers working on PDC-based hybrid engine. Goldmeer et al. [17] integrated a transfer function model into a thermodynamics system development and analysis tool to examine the performance of a hybrid PDC system. The results showed an increased efficiency of the PDC compared with the Brayton cycle. Tangirala et al. [18] developed a system level performance estimation model for a PDC-based hybrid engine cycle and carried out an experimental study using a multi-tube PDC turbine hybrid system to estimate the turbine performance under the steady constant pressure combustion mode vs. pulse detonation combustion mode. Test measurements over long duration tests showed no significant difference in turbine component efficiency under PDC-fired operation and steady flow operation. Rouser et al. [19] coupled the radial turbine of a Garrett GT28 automotive turbocharger to a PDC that uses two orifice plate obstacles for deflagration to detonation transition (DDT). The turbine was driven by steady deflagration and pulsed detonations using hydrogen fuel and the same combustor configuration. The specific work was improved by more than 70% with the PDC operating at 10 Hz and an overall equivalence ratio of 0.64. Experimental results showed that the specific work increased with the increase of the operating frequency and the equivalence ratio. The specific work was more sensitive to the operating frequency than the equivalence ratio. Sakurai et al. [20] used a single detonation tube to drive a full admission radial turbine, using hydrogen-air and a Shchelkin spiral for DDT. The thermal efficiency obtained was lower than that predicted from the thermodynamic analysis. The subsequent work[21] used two detonation tubes fired out of phase to achieve the combined operating frequencies as high as 80 Hz. It was shown that the thermal efficiency increased with the operating frequency; but it was still lower than the value of theoretical calculation, and the interaction between the two tubes appeared to have negative effect on the performance.

Previous studies have demonstrated the ability of a PDC to drive a turbine, however the system level practical performance of the PDC-based hybrid engine is lower than that predicted from the thermodynamic analysis. The critical issue, such as how to efficiently convert the tremendous energy in the high temperature and pressure pulse detonation to mechanical energy, has not been satisfactorily resolved.

This paper addresses the experimental findings and main factors on the power extraction of a turbocharger turbine driven by a PDC.

2. Experimental setup

A PDC–turbine hybrid system is designed and built by integrating an unvalved tube PDC system with a single-stage radial turbine. Fig. 1 shows a principle model of the experimental rig, which consists of a PDC, a turbocharger (centripetal turbine, centrifugal compressor), inlet, outlet, fuel system, gas system, detonation ignition and frequency control

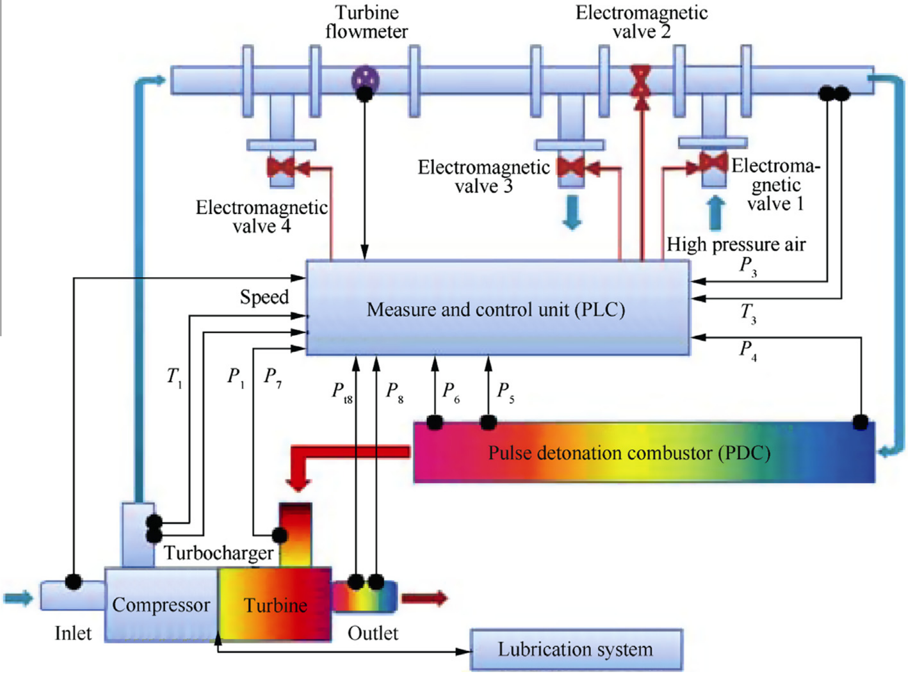


Fig. 1 Principle model of the experimental rig.

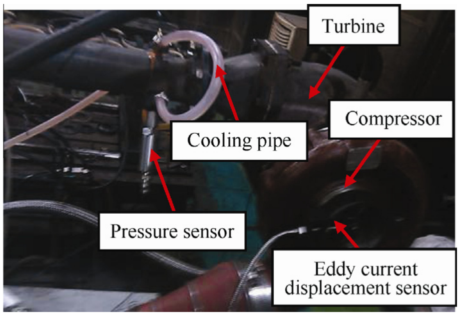


Fig. 2 Photo of J130A automotive turbocharger.

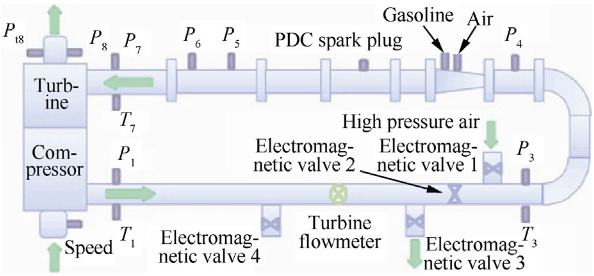


Fig. 3 Structure diagram of a PDC–turbine hybrid system.

system, lubrication system, data acquisition and control system. The turbine used in this study has 11 blades and is part of a J130A automotive turbocharger, as shown in Fig. 2. The J130A is equipped with a radial compressor with eight primary impeller blades and eight splitter blades. The center housing contains the shaft and dual ball bearing assembly.

The PDC is composed of inlet section, ignition section and detonation segment, which is 60 mm in diameter with a length of 1500 mm measured from the down-stream face of the fuel–air mixing element to the tube exit. This length is selected since it represents the distance in which gasoline-air detonation could be achieved using the implemented technology. A spiral DDT geometry is used in the detonation segment to assist the detonation process. The inlet section is designed to complete the air supply, fuel supply, and fuel atomization by a valveless adaptive way. When the detonation is formed, the pressure of the gas in the chamber is higher than that of the fuel and air, so they are prevented from flowing into the detonation chamber. When the detonation combustion products discharge from the detonation chamber, the pressure of the gas in the chamber is lower than that of the fuel and air mixture, and thus a new round of the filling cycle begins. A gear flow meter is used to measure the amount of the fuel, and a turbine flowmeter to measure the amount of the air. A spark plug is mounted approximately one diameter downstream of the fuel–air mixing element to allow a short distance for the fuel and air to mix prior to ignition. The thickness of the spark plug gasket can be changed to adjust the depth of spark plug inserted into the combustion chamber to ensure the optimum ignition position. The ignition frequency is controlled by a self-developed programmable logic controller (PLC).

3. Experimental scheme

The inlet section of PDC is connected to a high pressure tank. The PDC outlet is linked with the turbocharger turbine inlet, so the high velocity, temperature, and pressure detonation gas can radially flow into the turbine directly. The gas does work through expansion in the turbine, and discharges from the nozzle axially, which generates thrust at the same time. The turbine outputs shaft power to drive the compressor rotating. The air outside of the engine is inhaled into the compressor axially through the inlet, and discharges radially after being compressed. The test rig can work in two different modes: the auto inspiration mode, and the matching mode. In the auto inspiration mode, the electromagnetic valves 1 and 3 are closed, and the electromagnetic valve 2 is opened, so the outlet of the compressor is connected to the inlet of the detonation combustor. The compressed air can directly flow into the detonation chamber, and the PDC–turbine hybrid engine can work in the auto inspiration mode for a long time. In the matching mode, the air of the PDC is supplied by a high pressure tank, and the compressed air of the compressor is directly ejected into the atmosphere. This paper mainly studies the power extraction of the turbine driven by a PDC system, so the test rig works in the matching mode.

The structure diagram of a PDC–turbine hybrid system is shown in Fig. 3, from which the position of the sensors can be seen. A piezoresistive pressure sensor P_1 and a thermal resistance temperature sensor T_1 are installed at the compressor outlet to monitor the pressure and temperature of the compressed air. A piezoresistive pressure sensor P_3 and a thermal resistance temperature sensor T_3, installed at the air inlet of the engine, are used to measure the initial pressure and temperature of the high pressure air. Two piezoelectric pressure sensors P_5 and P_6 are installed at the end of the detonation chamber to measure the pressure of the detonation wave, and the propagation velocity can be calculated using the time of the detonation wave spreading from pressure sensors P_5 to P_6. The pressure and the velocity are used to determine whether the detonation waves are formed. A piezoelectric pressure sensor P_7 and a thermocouple temperature sensor T_7 are installed at the entrance of the turbine, and two piezoresistive pressure sensors P_8 and P_{t8} are installed at the outlet of the turbine, which are used to monitor the pressure of the gas before and after the turbine. An eddy current displacement sensor, installed at the compressor inlet, is used to measure the speed of the turbocharger rotor.

The test process is as follows. First a signal is sent out by the PLC to open the electromagnetic valves 1 and 3, and to close the electromagnetic valves 2 and 4, so the compressed high pressure air flows into the engine from the electromagnetic valve 1, and directly enters into the inlet section of the PDC after a bending segment, mixing with the fuel and air sprayed by the fuel supply system to complete the filling process. Second an ignition signal is issued by the PLC to a high-energy igniter to ignite the combustible fuel and air mixture by the spark plug. The detonation wave is formed after a DDT distance, and radially sprays into the turbine from the detonation chamber. Finally the high temperature and pressure gas does work by expansion in the turbine and discharges from the nozzle at last. At the same time, the high pressure air compressed by the compressor is discharged from the electromagnetic valve 3 into the atmosphere, then the next cycle starts.

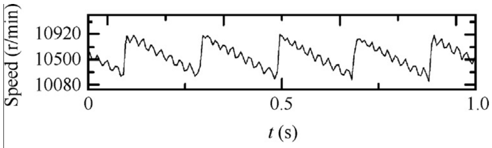
4. Experimental results

The test conditions of the PDC–turbine hybrid engine are shown in Table 1. The results of the benchmark test (III) are shown in Fig. 4. It can be seen that the turbine speed has a step increase after a detonation wave impaction, and then gradually declines in an approximately linear way. It is shown that the detonation wave has a strong impact, leading to the phenomenon that the turbine rapidly lifts from a low-speed to a high-speed. However, due to the instantaneity of the detonation wave, the pressure decays very fast, so the turbine power is greatly reduced after the detonation wave, and the turbine speed is gradually decreased under the effect of inertia and resistance until the next detonation wave arrives. It can be seen that the pressure curve p_1 has five peaks and the pressure peak is synchronous with the step increase of the turbine speed. It is shown that as the turbine speed increases, the capacity of the compressor improves, and the pressure of the compressed air rises. The pressure peaks of p_3 and p_4 are all surrounding 0.4 MPa, and for the pressure curve p_3, there is no obvious downward trend compared with p_4. This shows that the detonation wave has a strong return trend. In order to prevent the back airflow, there is a need to study a high frequency and reliable valve, which can meet the requirements of the engine intake and cut off the back pass airflow quickly when a detonation wave occurs. Through the comprehensive analysis of the detonation wave pressure p_5 and p_6, the time of each detonation wave spreading from p_5 to p_6 is obtained. The calculated averaged propagation velocity of detonation wave is 1192.3 m/s, and the pressure peaks of p_6 are all around 2.2 MPa. These indicate that detonation waves have been successfully generated. From the comparative analysis of p_7 and p_8 it can be seen that the pressure peak of the high temperature, pressure, and velocity detonation wave decreases from 2.0 to 0.3 MPa, which shows that the turbine has a strong attenuation on the detonation wave.

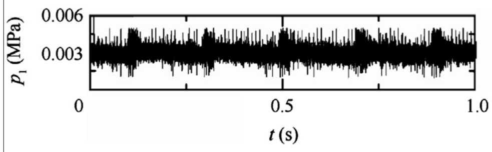
Fig. 5 shows the engine test results at the firing frequency of $f = 5$ Hz and the equivalence ratio of $\Phi = 0.93$–1.18. The uncertainty bar is computed by propagation of uncertainty analysis and includes the uncertainty of the measuring instrument. It is shown that the flow rate of the compressor and the turbine speed have the same trend with the equivalence ratio. When the equivalence ratio is 1.01689 (test condition II), the turbine speed reaches the maximum value of

Table 1 Experimental run conditions.

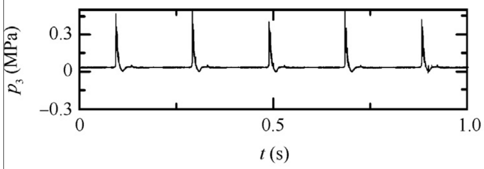
Test condition	Frequency (Hz)	High pressure airflow rate (kg/h)	Gasoline flow rate (mL/s)	Equivalence ratio
I	5	115.7	2.8	0.93438
II	5	121.5	3.2	1.01689
III	5	128	3.4	1.02558
IV	5	121.3	3.7	1.17772



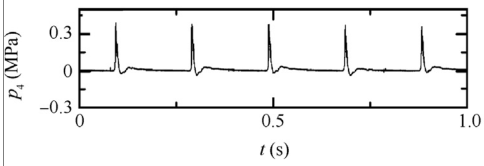
(a) Turbine rotor speed



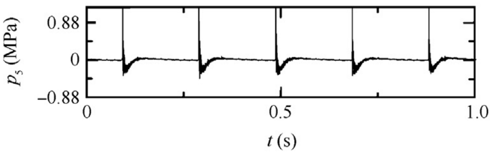
(b) Pressure at sensor P_1



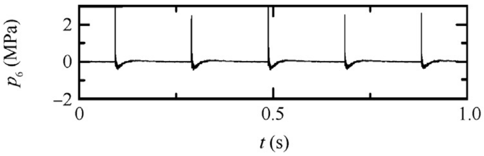
(c) Pressure at sensor P_3



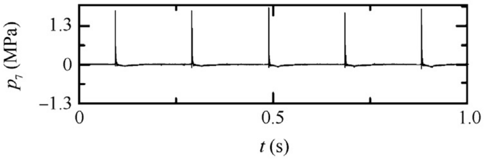
(d) Pressure at sensor P_4



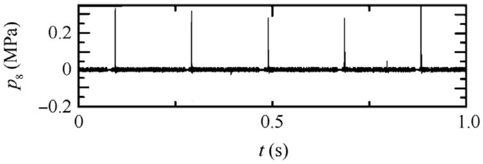
(e) Pressure at sensor P_5



(f) Pressure at sensor P_6

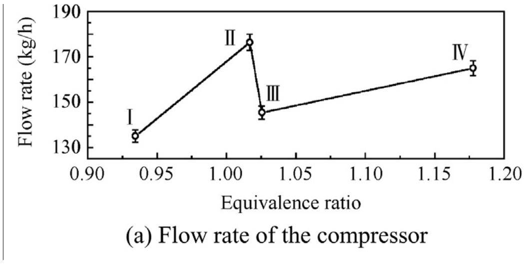


(g) Pressure at sensor P_7

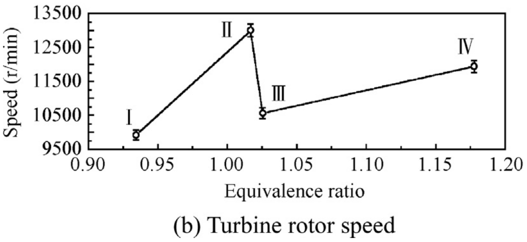


(h) Pressure at sensor P_8

Fig. 4 Benchmark test (III) results.

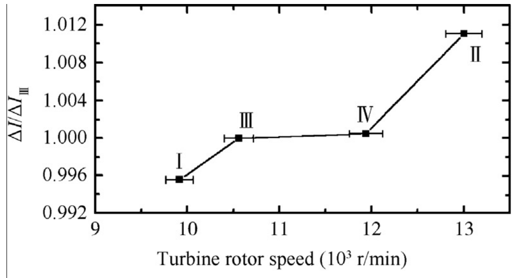


(a) Flow rate of the compressor

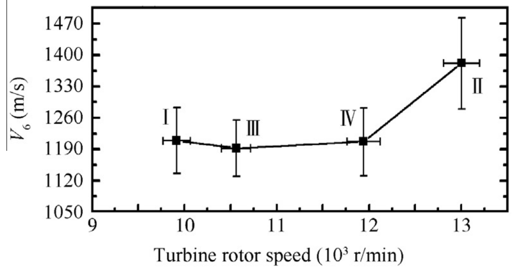


(b) Turbine rotor speed

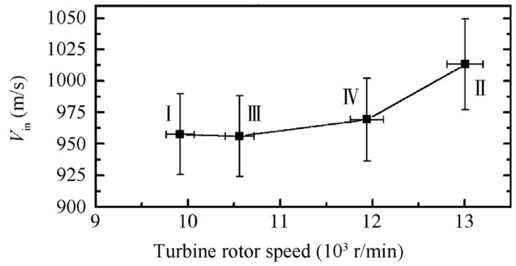
Fig. 5 Experiment results of four test conditions.



(a) Momentum difference



(b) Gas velocity at PDC outlet



(c) Gas velocity at tuibine inlet

Fig. 6 Detonation wave pressure and velocity influence on turbine speed.

(13003.9 ± 195) r/min, and the flow rate of the compressor is up to the maximum value of (176.4 ± 3.5) kg/h.

To further analyze the reasons, considering that the turbine speed is only related to the turbine inlet and outlet conditions, three parameters are defined as shown in Eq. (1): momentum difference per unit area between the turbine inlet and outlet (ΔI), the velocity of the detonation wave at the PDC outlet (V_6), the velocity of the detonation wave at the turbine inlet (V_{in}). The momentum difference ΔI is mainly used to estimate the force of the gas acting on the turbine blades, the velocity V_6 is used to measure the strength of the detonation wave, and the velocity V_{in} is primarily used to measure the size of the gas kinetic energy at turbine inlet.

$$\begin{cases}\Delta I=\frac{\Delta F}{A}\cdot t=\int_0^t(p_7-p_8)\mathrm{d}t\\ V_6=l_{56}/t_{56}\\ V_{\mathrm{in}}=l_{67}/t_{67}\end{cases}\tag{1}$$

where ΔF is the force difference between turbine inlet and outlet; p_7 and p_8 are the pressures at the turbine inlet and outlet, respectively; l_{56} is the distance between pressure sensors P_5 and P_6; t_{56} is the time of detonation wave spreading from P_5 to P_6, and l_{67} and t_{67} are defined in a similar way as l_{56} and t_{56}.

With analysis from the energy equation, the actual shaft work extracted from the gas by the turbine is

$$\begin{aligned}W&=\int_0^t\left(c_pT_7^*-c_pT_8^*\right)\mathrm{d}t\\&=\int_0^t\left(c_pT_7-c_pT_8+\tfrac{1}{2}V_7^2-\tfrac{1}{2}V_8^2\right)\mathrm{d}t\\&=\int_0^t\left(c_p\frac{p_7}{\rho_7R}-c_p\frac{p_8}{\rho_8R}+\frac{1-(A_7\rho_7/A_8\rho_8)^2}{2}V_7^2\right)\mathrm{d}t\end{aligned}\tag{2}$$

where c_p is the specific heat at constant pressure; T^* is the total temperature; T is the static temperature; V is the velocity of the gas, ρ is the density, and R is the gas constant; subscripts 7, 8 respectively represent the turbine inlet and outlet.

If the area of the turbine inlet is equal to the area of the turbine outlet, and assuming the density of the gas changes little before and after the turbine, Eq. (2) can be simplified to:

$$W=\frac{c_p}{\rho_7R}\int_0^t(p_7-p_8)\mathrm{d}t\tag{3}$$

Comparing Eqs. (1) and (3), it can be found that the actual shaft work is directly decided by the momentum difference.

In order to facilitate comparative analysis, the momentum difference ΔI is normalized by the value in benchmark test

Table 2 Experiment results of four test conditions.

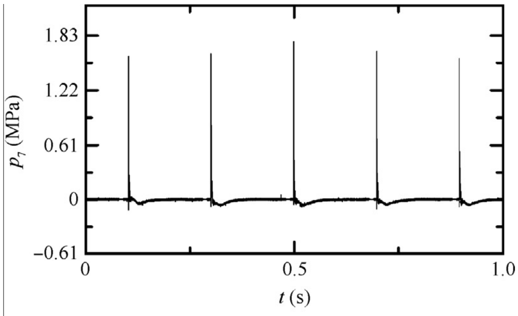
Test condition	Equivalence ratio	Compressor flow rate (kg/h)	Turbine rotor speed (mL/s)	$\Delta I/\Delta I_{\mathrm{III}}$	V_6 (m/s)	V_{in} (m/s)
I	0.93438	135	9918.3	0.99563	1209.3	957.5
II	1.01689	176.4	13003.9	1.01105	1381.6	1013.3
III	1.02558	145.5	10560.9	1	1192.3	956.0
IV	1.17772	165	11940.3	1.00049	1207.0	969.3

III. The experiment results are shown in Table 2. It can be seen that the turbine rotor speed reaches the maximum value when the momentum difference ΔI, detonation wave velocity V_6 and $V_{\rm in}$ are the largest.

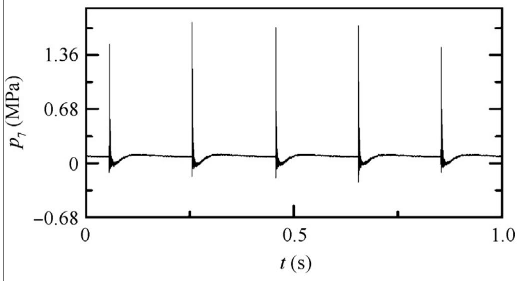
Fig. 6 shows the effect of the pressure and velocity of the detonation wave on the turbine speed. It can be found that the turbine speed is affected by the momentum difference ΔI, detonation wave velocity V_6 and $V_{\rm in}$, but ΔI is more important than the others. For example, compared the engine test condition I with III, the engine turbine rotor speed is supposed to be decreased because V_6 and $V_{\rm in}$ are declined, but in fact it increases in an upward trend due to the increase of the momentum difference ΔI. So it is reasonable to obtain two methods of improving the speed of the turbine rotor: one is to choose an optimal equivalence ratio of fuel and air mixture in order to generate stable and strong detonation waves, which have characteristics such as high velocity, pressure and temperature. The other method is to design an optimal transition structure between the detonation chamber and the turbine. The optimized structure ensures that the integration of the pressure at the turbine inlet along the time axis is the maximum, namely, the area of the pressure curves enclosed is the largest.

Fig. 7 shows the comparison of the pressure p_7 at four sets of test conditions. It can be seen that p_7 peak of test condition II is not the largest in the four groups of trials, but the turbine speed and the flow rate of the compressor are the maximum, which indicates that the pressure peak of p_7 has little effect on the turbine rotor speed.

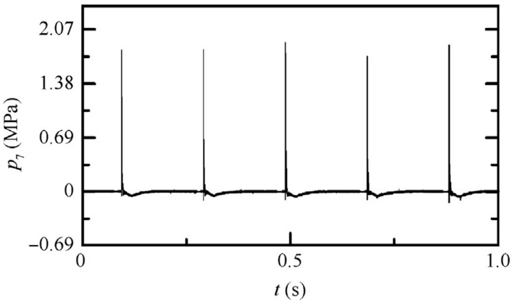
For the further study of the relationship between the pressure peak difference and the momentum difference, four test results are analyzed, as shown in Table 3, from which it can be seen that pressure peak difference between the turbine inlet and outlet continuously increases with increasing the equivalence ratio. By comparing the pressure peak difference and the momentum difference, it can be found that the momentum difference ΔI does not increase with the pressure peak difference, and the maximum of the momentum difference does not correspond to the maximum or minimum of the pressure peak difference either.



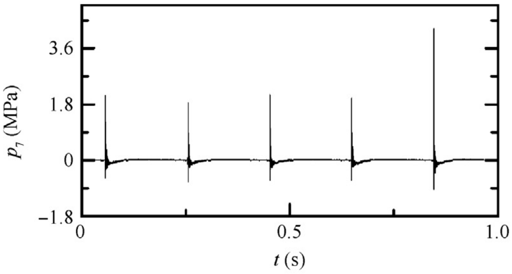
(a) Test condition Ⅰ



(b) Test condition Ⅱ



(c) Test condition Ⅲ



(d) Test condition Ⅳ

Fig. 7 Turbine inlet pressure p_7 at four sets of test conditions.

5. Conclusions

(1) An experimental study on the power extraction of a turbine driven by a pulse detonation combustor is presented in this paper. It is found that when the engine ignition frequency is 5 Hz, the optimal equivalence ratio of fuel and air mixture is 1.01689. At that test condition

Table 3 Relationship between pressure peak difference and momentum difference.

Parameter	Test condition			
	I	II	III	IV
Equivalence ratio	0.93438	1.01689	1.02558	1.17772
Pressure peak average $\bar{p}_7$ (MPa)	1.644127	1.630861	1.82535	2.456166
Pressure peak average $\bar{p}_8$ (MPa)	0.270329	0.192495	0.31774	0.379801
$\bar{p}_7 - \bar{p}_8$	1.373797	1.438365	1.50760	2.076364
$\Delta I/\Delta I_{\rm III}$	0.99563	1.01105	1	1.00049

the speed of the engine turbine reaches the maximum, and the flow rate of the compressor is also up to the highest.

(2) Two key factors that affect the speed of the turbine are found. One is the momentum difference per unit area between the turbine inlet and outlet. The other is the velocity of the gas at the turbine inlet. The difference of pressure peak between turbine inlet and outlet has little effect on the turbine speed.

(3) The indirect factors that affect the speed of the turbine are the equivalence ratio of fuel and air mixture and the transition structure between PDC and turbine. The equivalence ratio mainly affects the velocity, intensity and stability of the detonation wave, while the transition structure is mainly to change the pressure curve of the detonation wave. The momentum difference per unit area between the turbine inlet and outlet can be enlarged through designing an appropriate transition structure. Therefore mastering the engine optimum operating point and designing an optimal transition structure are essential for the PDC–turbine hybrid engine. These results are very encouraging and further work is recommended using a rig specifically designed the transition structure for performance study.

Acknowledgement

This work is supported by National Natural Science Foundation of China (Grant No. 50906072).

References

1. Ma F, Choi JY, Yang V. Propulsive performance of air breathing pulse detonation engines. *J Propul Power* 2006;**22**(6):1188–203.
2. Harris PG, Stowe RA, Ripley RC, Guzik SM. Pulse detonation engine as a ramjet replacement. *J Propul Power* 2006;**22**(2):462–73.
3. Heiser WH, Pratt DT. Thermodynamic cycle analysis of pulse detonation engines. *J Propul Power* 2002;**18**(1):68–76.
4. Kentfield JAC. Thermodynamics of air breathing pulse-detonation engines. *J Propul Power* 2002;**18**(6):1170–5.
5. Goldmeer J, Tangirala VE, Dean AJ. System-level performance estimation of a pulse detonation based hybrid engine. *J Eng Gas Turbines Power* 2008;**130**(1):011201.
6. Fickett W, Davis WC. *Detonation: theory and experiment*. Mineola, NY: Dover Publications; 2000.
7. Roy GD, Frolov SM, Borisov AA, Netzer DW. Pulse detonation propulsion: challenges, and current status, and future perspective. *Prog Energy Combust Sci* 2004;**30**(6):545–672.
8. Powers J, Frolov SM. Perspectives on detonation-based propulsion. *J Propul Power* 2006;**22**(6):1153–4.
9. Santoto RJ, Yang V, Shepherd JE, Law CK. A multidisciplinary study of pulse detonation engine propulsion. For Award number: ONR N00014-99-1-0744; 2003.
10. Knox BW, Forliti DJ, Stevens CA, Hoke JL, Schauer FR. A comparison of fluidic and physical obstacles for deflagration-to-detonation transition. In: *49th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*; 2011 Jan 4–7; Orlando, Florida; 2011.
11. Paxson DE. A simplified model for detonation based pressure-gain combustors. In: *46th AIAA/ASME/SAE/ASEE joint propulsion conference & exhibit*; 2010.
12. Ajmani K, Kundu K, Penko PF. A study on detonation of jet-a using a reduced mechanism. In: *48th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*; 2010 Jau 4–7; Orlando, Florida; 2010.
13. Nielsen JM, King PI, Schauer FR, Stevens C, Hoke JL. Detonation propagation through ducts in a pulsed detonation engine. In: *49th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*; 2011 Jau 4–7; Orlando, Florida; 2011.
14. Kasahara J, Takazawa K, Arai T, Tanahashi Y, Chiba S, Matsuo A. Experimental investigations of momentum and heat transfer in pulse detonation engines. *Proc Combust Inst* 2002;**29**(2):2847–54.
15. Peng CX, Fan W, Zhang Q, Yuan C, Chen WJ, Yan CJ. Experimental study of an air-breathing pulse detonation engine ejector. *Exp Therm Fluid Sci* 2011;**35**(6):971–7.
16. Chen WJ, Fan W, Zhang Q, Peng CX, Yuan C, Yan CJ. Experimental investigation of nozzle effects on thrust and inlet pressure of an air-breathing pulse detonation engine. *Chin J Aeronaut* 2012;**25**(3):381–7.
17. Goldmeer J, Tangirala V, Dean A. Systems-level performance estimation of a pulse detonation based hybrid engine. ASME Paper, GT-2006-90486; 2006.
18. Tangirala VE, Rasheed A, Dean AJ. Performance of a pulse detonation combustor-based hybrid engine. ASME Paper, GT-2007-28056; 2007.
19. Rouser KP, King PI, Schauer FR, Sondergaard R, Hoke JL. Parametric study of unsteady turbine performance driven by a pulse detonation combustor. In: *46th AIAA/ASME/SAE/ASEE joint propulsion conference & exhibit*; 2010 Jul 25–28; Nashville, TN; 2010.
20. Sakurai T, Obara T, Ohyagi S, Murayama M. Experimental study of pulse detonation turbine engine toward power generator. In: *international colloquium on the dynamics of explosions and reaction systems*; 2005.
21. Tsuji T, Shirakawa S, Yoshihashi T, Obara T, Ohyagi S. Interaction between two cylinders in a pulse detonation engine. *Int J Energ Mater Chem Propul* 2009;**8**(6):489–500.

Li Xiaofeng is a Ph.D. student at School of Power and Energy, Northwestern Polytechnical University. He received the B.S. and M.S. degrees from Northwestern Polytechnical University in 2008 and 2011, respectively. His area of research includes combustion and flow of aero-engine.

Zheng Longxi is a professor and Ph.D. supervisor at School of Power and Energy, Northwestern Polytechnical University. He is devoted to the study of combustion, propulsion and pulse detonation engines.