Applied Thermal Engineering 113 (2017) 426–434

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental investigation on interactions between a two-phase multi-tube pulse detonation combustor and a centrifugal compressor

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HIGHLIGHTS

- A new compressor-PDC integrated system was designed and successfully tested.
- The operability of the compressor-PDC system is proved for the first time.
- The interaction between the compressor and the PDC are revealed.

ARTICLE INFO

Article history:
Received 20 July 2016
Revised 8 October 2016
Accepted 29 October 2016
Available online 31 October 2016

Keywords:
Two-phase multi-tube pulse detonation combustor
Compressor
Experimental
Pulse detonation turbine engine

ABSTRACT

In order to carry out an experimental investigation on interactions between the compressor and the pulse detonation combustor (PDC) in a pulse detonation turbine engine (PDTE), an integrated system consisted of a four-tube PDC and a centrifugal compressor nominally rated for 1.05 kg/s, 70,000 RPM was set up and tested. The compressor was directly connected to the four-tube PDC. A radial turbine driven by a traditional combustor was used as the compressor's power input system to simulate the operating conditions of the compressor in a practical PDTE. Gasoline was used as fuel and compressed air from the compressor was supplied into the four-tube PDC. The Operability of the system is proved under the simultaneously and the sequentially firing patterns at frequencies from 20 Hz to 30 Hz. Pressure oscillations at the compressor exit are observed. Interactions between the compressor-PDC are revealed through the comparison of the compressor's parameters under different operating modes. The results indicate that the pressure oscillations will have a throttling effect on the compressor and change its operating points. Additionally, the firing of the four-tube PDC will push the operating line of the two components towards the surge line of the compressor.

1. Introduction

It is well known that the energy release process in most of the propulsion system is based on deflagration. However, detonation is a more efficient method of burning the fuel–oxidizer mixture when compared with deflagration due to the pressure-gain combustion and the supersonic propagation characteristics. Extensive efforts have been implemented to develop detonation-based propulsion systems such as pulse detonation engine (PDE), rotating detonation engine (RDE) and pulse detonation turbine engine (PDTE) since the 1940s [1–5]. In the PDTE's concept, the traditional deflagration combustor is replaced by the pulse detonation combustor (PDC). Performance calculations of the PDTE indicate potential performance improvements on specific thrust and specific fuel consumption when compared with the traditional turbine engine [6–8]. However, there will be interactions between the PDC and the upstream compressor or the downstream turbine when the steady combustor in the traditional turbine engine is replaced by the cyclic operated PDC. When the highly unsteady shock-induced pulse detonation wave enters into the turbine, the interactions between the detonation wave and the turbine blade will affect both the turbine efficiency and the PDC's operability. Additionally, the pressure-gain combustion process and the cyclic operated characteristics of the PDC will cause pressure oscillations at the PDC inlet. The compressor or the fan will be operated under a cyclic oscillated outlet condition. The compressor efficiency will be affected and even more severely, a stall will happen inside the compressor or the fan.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.10.188
1359-4311/

In the past decades, there were many studies about the interactions between the PDC and the turbine. Hoke et al. [9,10] conducted several tests on a dual-tube PDC integrated with a turbo-charge in order to demonstrate the possibility of self-aspiration by using the turbine driven compressor to supply air into the detonation combustor. In their report, a 25-min self-aspirated running test was performed. Lately, more detailed tests were carried out to study the performance of the radial turbine powered by pulsed detonations [11,12]. Flow measurements of pressure, temperature and velocity were carried out at the inlet and exit of the turbine [13]. The results indicated that the turbine was able to extract the unsteady power in an effective manner. Rasheed et al. [14,15] developed a PDC-turbine combined system consisted of eight PDC tubes arranged in an annular configuration integrated with a single-stage axial turbine nominally rated for 10 lbm/s, 25,000 RPM, and 1000 hp. The system was successfully tested with three firing patterns using ethylene–air mixtures. Analysis of the performance data suggested that the hybrid engine performance benefit could be realized with further development. Glaser et al. [16–18] also set up a similar system consisting of six PDC tubes and a small axial turbine. It was found that the PDC driven turbine had comparable performance to that of a steady burner driven turbine performance across the operating map of the turbine. In the further research, a new axial turbine was studied under close-coupled, out-of-phase, multiple-admission pulsed air flow to approximate turbine behavior under pulsed detonation inflow [19].

The above studies show that interactions between the PDC and the turbine had been investigated in detail. However, there are little investigations on the interactions between the PDC and the upstream components like a compressor up until now. Although experimental and numerical analyses on interactions between the inlet and the pulse outflow conditions have been carried out by several research institutes [20–23] and the inlet remained started for all the test conditions, the compressor is more likely to suffer the stall problem under the oscillated outflow condition.

Recently, experimental investigations on a pulse detonation turbine prototype engine have found out that the maximum specific thrust is 27% higher than that of the traditional engine based on ideal Brayton cycle [5], but the interactions between the compressor and PDC were not discussed. Performance calculations of Mawid et al. [6] also demonstrated that for the PDC operating at a frequency of 100 Hz and higher, the thrust and specific thrust of a pulse detonation turbofan engine can nearly be twice as much as those of the conventional afterburning turbofan engine. However, they also pointed out that the operation of the engine fan and the PDC warranted further investigations.

The present paper will focus on the interactions between the compressor and the PDC. A centrifugal compressor directly integrated with a four-tube PDC system was developed and experimental investigations on the interactions between the two components were addressed. This research is a continuation of the previous research on the operation of the four-tube PDC [24,25]. The centrifugal compressor was designed at the upstream of the four-tube PDC to supply compressed air to the four-tube PDC. Operation of the compressor-PDC system is carried out under two firing patterns: all tubes firing simultaneously and all tubes firing sequentially. The operability of the system under the two firing patterns is studied. The back pressure waves and the pressure oscillations at the compressor exit are quantified and compared. The interactions between the compressor and the PDC are revealed. The present studies will provide some theoretical and experimental bases to accelerate the application of the pulse detonation turbine engine.

2. Experimental setup

A scheme of the experimental setup is shown in Fig. 1. A centrifugal compressor nominally rated for 1.05 kg/s, 70,000 RPM and pressure ratio of 3.5 was installed at the upstream of the four-tube PDC. A double-torsion-line flow-meter was connected to the inlet of the compressor to measure the air flow rate. A power input system was used to drive the compressor. In the traditional turbine jet engine, the compressor is connected to a turbine through a shaft and the compressor rotates with the turbine driven by a constant pressure combustor. In the present paper, a radial turbine driven by a traditional combustor was used as the power input system to simulate the operating conditions of the compressor in a practical PDTE. The turbine was connected to the radial compressor through the same shaft. The turbine provided shaft power for the compressor by extracting energy from the combustion gases flowing out of the traditional combustor.

The compressor exit was connected to the four-tube PDC through a connection section. The length and the inner diameter (ID) of the connection section were 0.1 m and 0.09 m, respectively. The four-tube PDC were exactly the same as the apparatus presented in Ref. [24] and Ref. [25], which consisted of a transition section, a common air inlet and four single tube pulse detonation combustors. The compressed air was delivered into the common air inlet through the transition section and uniformly divided between each tube, guided by a big entrance cone placed at the center of the common air inlet. Each single tube pulse detonation combustor consisted of four different sections: a single tube inlet, a fuel supply and mixing chamber, an ignition chamber and a detonation chamber.

Gasoline was fed into each fuel supply and mixing chamber by four fuel pipes. Four twin-fluid air-assist atomizers were used for gasoline injection. The gasoline/air mixture was ignited by an automotive spark plug located in the middle of the ignition chamber. The ignition energy was less than 50 mJ. An in-house designed ignition system was used to control the firing patterns and the frequency.

High frequency pressure transducers were installed along the flow path of each tube. At the end of each detonation chamber, high frequency piezoelectric pressure transducers (P_1–P_8) were installed at a spacing of 0.05 m to verify the successful initiation of the detonation waves (Fig. 1). Piezoresistive pressure transducers (F_1–F_4) were placed in each single tube inlet to capture the back pressure wave dynamics during PDC firing operation. Another piezoresistive pressure transducer (F_0) was positioned on the top of the air plenum chamber to capture back pressure waves in the common air inlet. F_0 was directly in-line with tube 1. One piezoresistive pressure transducer (F_{C1}) was installed at the middle of the connection section to measure the total pressure at the compressor exit and another (F_{C2}) was used to monitor the total pressure of back pressure waves at the compressor exit. The rotor speed of the compressor was measured by a speed measurement system. The system consisted of an eddy current displacement sensor and an in-house designed signal control and transform system, which is presented in Fig. 2. There was a hex nut installed at the end of the compressor rotor. The eddy current displacement sensor was used to measure the displacement change of the hex nut when it rotated with the rotor. The sensor would detect six displacement changes when the rotor rotated by one cycle. Then, the signal was recorded and transformed into the speed of the rotor through the signal control and transform system. All these data was monitored and collected through the DEWE3020 high-speed data acquisition system with a total of 16 channels and the sampling rate was 200 K samples/s.