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Research Paper

Experimental investigation of an air-breathing pulse detonation turbine prototype engine

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HIGHLIGHTS

- An air-breathing pulse detonation turbine prototype engine was investigated by experiments.
- Two ignition methods on the engine were analyzed and discussed.
- Component characteristics were analyzed.
- Propulsive performances were given which show advantages over turbojet based on ideal Brayton cycle.

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ABSTRACT

This article presents a prototype system of pulse detonation turbine engine which consists of two pulse detonation chambers (PDCs) and a turbocharger. Synchronous and asynchronous ignition methods are investigated with ignition frequency up to 20 Hz. Equivalence ratios are controlled around unity. Pressures in the PDCs show different detonation characteristics between these two ignition modes. Pressures upstream of the PDCs are also given. Detailed analyses of these pressure histories show that the two PDCs are coupled and these coupling effects become stronger for asynchronous ignition. Pressure downstream of the compressor is measured and three different compressor pressure ratios are defined according to this pressure. Pressure ratios and rotational speed are given as functions of ignition frequency and air flow rate which also reflect differences between these two ignition modes. Finally, the propulsive performances of the air-breathing pulse detonation prototype engine with synchronous and asynchronous ignition modes are provided. The maximum specific thrust of the system reaches 753 N s/kg which is 27% higher than that of the traditional engine based on ideal Brayton cycle.

1. Introduction

Pulse detonation engines (PDEs) are unsteady propulsion systems that produce thrust or power by using repetitive detonations [1]. According to Chapman–Jouguet (CJ) theory, the CJ detonation point corresponds to the global minimum entropy generation along the Hugoniot curve [2]. Therefore, the ideal PDE cycle shows increased thermodynamic efficiency greater than Humphrey and Brayton cycles and potentially PDEs have better propulsive performance than the traditional engines [3,4]. Since the propulsive concept of PDE was proposed by Nicholls [5], many configurations of PDEs have appeared. Some of them rely directly on the impulse thrust of the gases exhausted from pulse detonation chamber (PDC) [1]. Advanced concepts [6–10] are proposed after 2000 where the standard continuous flow combustor of gas turbine engine is replaced with multiple pulsed detonation chambers. Although specific concepts vary in their implementation, a common feature incorporates the idea of exhaust from PDC driving a downstream turbine and the engine with this feature can also be called a pulse detonation turbine engine (PDTE) [11].

Early research works [12–14] of the PDTE concentrated on the theoretical propulsive performance of the engine and the potential advantages of the PDTE were provided. Recently, more studies have been performed on PDC-turbine system employing axial/centrifugal flow turbines, with emphasis on operability, wave interactions, performance and the mechanical response due to pulsed detonations [15,16]. Unlike the previous works, the present paper reports on the hybrid performance of an air-breathing compressor-PDC-turbine system, in which a double-tube PDC is coupled with an automotive-based turbocharger. This type of hybrid system was first investigated by Hoke et al. [17]. Based on

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this type of system, many researchers [18–20] have studied the performance of a PDC supplying a centrifugal turbine coupled to a centrifugal compressor, especially focusing on the turbine efficiency and the factors effecting output power of turbine. In this study, the air compressed by the centrifugal compressor is supplied to the PDCs and the hybrid system operates in the air-breathing mode. Therefore, a pulse detonation turbine prototype engine is formed. Influences of the ignition signal modes, synchronization and asynchronization, on the working characteristics of the prototype engine are investigated, such as detonation characteristics, compressor pressure ratio, rotational speed, etc. Propulsive performances of the prototype engine are also determined.

2. Experimental setup

A. PDC-turbocharger hybrid system

The PDC-turbocharger hybrid system consists of a double-tube PDCs, turbocharger, linkage sections, air intake system and nozzles as shown in Fig. 1. The turbine inlet of turbocharger is connected to the downstream end of the PDCs by a V-type connecting section while the turbine outlet is connected to a convergent nozzle to enhance the propulsive performance. The compressor outlet of turbocharger is assembled to the air duct system. The air duct system is L-shaped and split into two air outlets to connect with the double-tube PDCs via a V-type connecting section. The air duct system has two air inlets and two air outlets. As mentioned before, one air inlets and two air outlets are applied to connect the turbocharger and PDCs respectively. The other one air inlet (T-structure in the Front view of Fig. 1) is connected to a storage tank via an on–off solenoid valve which is used to control the working mode of the hybrid system. When the PDC-turbocharger hybrid system is started, the solenoid valve is set to open to allow air to enter from the storage tank. After the hybrid system achieves a self-sustaining working state, the solenoid valve is shut off. Then the hybrid system will only use the compressed air from the compressor of the turbocharger to run, which is in an air-breathing working mode.

The PDC with a length of 1680 mm consists of intake section, mixing section and detonation section. The intake section is 100 mm in diameter with a length of 250 mm. A cone with a diameter of 26 mm is used as an inflow diverter. A twin-fluid a ir-assist atomizer (schematic was shown in Ref. [21]) used for gasoline injection is installed at the downstream end of the cone. Pressure-air and liquid gasoline are forced into the atomizer through two pipelines in the cone. An aerodynamic valve (designed according to the Ref. [21]) is positioned in this section to damp the backflow. The fuel spray and the main airflow are designed to mix in the 130-mm-long mixing section. This mixing section steps down from Φ100 mm to Φ60 mm. The detonation section with a diameter of 60 mm can be further divided into a 140-mm-long ignition section and a 1160-mm-long deflagration-to-detonation (DDT) section. The DDT process is enhanced by Shchelkin spiral.

The calibration state of the turbocharger is a mass flow rate is 0.7 kg/s with compressor pressure ratio of 2.06 and a rotation speed of 55,000 r/min. There is a converging nozzle installed at the exit of the turbine. The nozzle is 20 cm long with the diameter of the nozzle's entrance equal to 12 cm. And the diameter of the nozzle's exit is 8 cm.

B. Instrumentation

The PDC-turbocharger hybrid system is instrumented to measure relative static/total pressures, rotational speed, mass flow and thrust. The pressure transducers, which are embedded in side walls, namely Pt1, P2, P3, P4 and P5 are shown in Fig. 1. Transducers Pt1 and P2 are mounted along the air duct system. Transducer Pt1 is used for measuring the exit stagnation pressure of the compressor while P2 is for measuring the reverse-propagating pressure wave. Transducers P3–P5 are located along the PDCs with P3 positioned downstream of the aerodynamic valve. Each PDCs have two

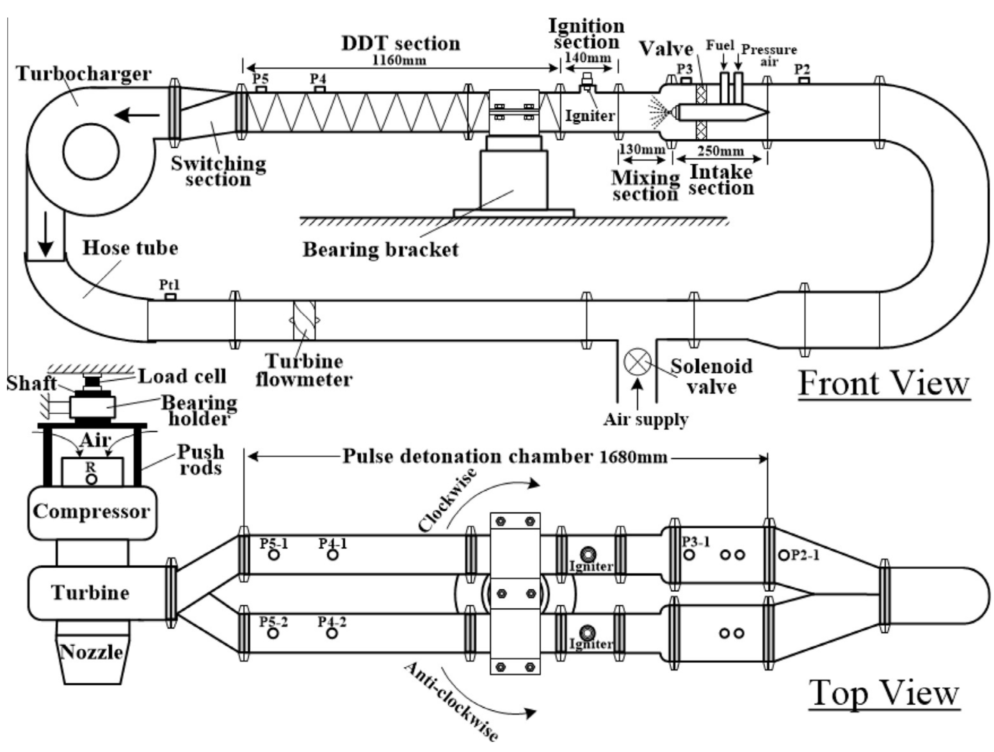

Fig. 1. Experimental setup of PDCs-turbocharger hybrid system.