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Experimental study of a hydrogen-air rotating detonation engine with variable air-inlet slot

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ABSTRACT

Rotating detonation engines have attracted considerable attentions in recent years. In this study, the experiments of initiating rotating detonation waves were performed on a H_2/air rotating detonation wave with the variable air-inlet slot. The results showed that the stability of detonation-wave pressure and velocity both initially increased and then decreased with the increase of slot width, and it could improve the stability of detonation-wave velocity via increasing the equivalence ratio. The intensity of reflected wave was strong for the tests of $d = 0.5$ mm, which leaded to the advance ignition of fresh mixture and a velocity deficit reaching up to 20%. The strong interaction between air plenum and combustor and bad mixing effect may be the reasons of forming unstable detonation wave for the tests of large-scale slots. The air-inlet slot of $d = 1$ mm, which got a best experiment results relative to other tests, had a wide equivalence-ratio scope to produce stable detonation wave.

Introduction

At present, the power and propulsion systems based on detonation mainly are pulse detonation engines (PDEs) [1,2], standing detonation engines (SDEs) [3] and rotating detonation engines (RDEs) [4,5]. Comparing with the PDEs, the RDEs have advantages of a high operation frequency, stable thrust, small axial size, and the ability to produce continuous detonation waves with the only one-time ignition, i.e., RDEs rely on the ignition systems a little. Comparing with the SDEs, the RDEs can work in the condition of wide flight mach numbers, and have hardly any limits of mach numbers. Besides, RDEs can perform thrust vector control via adjusting the mass flow rate of reactants in different azimuthal locations. Therefore, the RDEs have a promising application in the field of aerospace and weaponry. RDEs have attracted considerable attentions in recent years, and the related researches have been carried out in many countries, such as Russia, America, Poland, France, China, Japan, Singapore and South Korea [6,7].

Research on RDEs mainly includes fuel and oxidiser compositions [8–10], the structures of the rotating detonation wave (RDW), the working modes and self-sustained mechanism [11–15], the ignition methods [16–19], the effects of the reactant-injection conditions on the RDW propagation characteristics [20,21], the effects of the RDW on the plenum-working characteristics [22], the structures of rotating detonation combustor (RDC) [10,23], and the thrust performance [20,24,25] and application [26–29]. The premise to ensure RDEs operate steadily is obtaining stable RDWs; however, the

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conditions are strict. The stability of RDWs easily has a switcheroo to produce an unstable phenomenon, even extinguishing. There are many instabilities of RDWs. Anand et al. [12] revealed four fundamentally different instabilities—chaotic instability, waxing and waning instability, mode switching and longitudinal pulsed detonation instability—visa a large number of experiments. Peng et al. [17] found a phenomenon that detonation-wave intensity appeared strong weak alternately in experiments. Liu et al. [30] found the detonation-wave peak values changed periodically and thought this unstable phenomenon was related to the variation of propellant's mass flow rate.

The injection structure of RDEs has a direct influence on the detonation-wave propagation stability. Anand et al. [13] investigated the operation performance with three fuel-injection structure and the results showed that the fuel plate with the highest length-to-diameter ratio exhibited lean operation devoid of transitional or pop-out events; and further testing showed that the increase of air injection area increased the number of pop-out events. Frolov et al. [20] found that the number of detonation wave would be decreased with the increase of air-inlet slit width. Rankin et al. [14] revealed that the wave front was more concave as the air injection area was increased from low to intermediate values via a representative optically accessible RDE.

In this study, the experiments of initiating RDW were performed on a H_2/air RDE. The aim of this work is to study the RDW propagation characteristics via gradually changing the width of air-inlet slot, and analyze the reasons of producing the stable or unstable detonation wave. Finally, the experiment got an optimum slot with stable detonation wave in combustor. This work hoped to provide a reference for the research of RDEs.

Experimental facilities

The experimental system is composed of a hydrogen supply system, an air supply system, an RDE, an ignition device, a data-acquisition system, and a timing-sequence control system, as shown in Fig. 1.

The injection modes of oxidiser and fuel are slot-slot type, slot-orifice type and orifice-orifice type; among them, the slot-orifice type is generally used in experiments. A slot-orifice injection configuration is used in experiments for this study, as shown in Fig. 1. Hydrogen, which is used as fuel, is injected into chamber through 120 orifices uniformly distributed in front of combustor, and air, which is functioned as an oxidiser, is injected into combustion chamber through an annular slot. The width of air-inlet slot (d) could be changed by the slot spacer at the front end of center body. Six widths of air-inlet slot ($d = 0.5$, 1, 1.5, 2, 2.5, 3 mm) are selected for experiments to investigate the detonation-wave propagation stability.

The structure of combustion chamber in RDE is different with other propulsion system. It is demonstrated that the structure patterns, which can be used as combustion chamber, are disk-shaped combustor [31], annular combustor and hollow combustor [32]; among them, the annular combustor is used the most and has a good operation performance. An annular combustor, with an inner diameter of 124 mm and an outer diameter of 136 mm, is used in this experiment.

The RDW can be successfully initiated by the pre-detonator, thermal-jet tube, low-energy or high-energy spark plug, etc. The initiation way of detonation wave only influences on its formation process, and the operation characteristics of the engine model are independent of the ignition device [16]. Peng [17] obtained the ignition success rate of 94% using ordinary spark-plug device in experiments. Besides, the spark-plug device has advantages of easy to installation and simple control. The ignition energy of spark-up device is 50 mJ using in this experiment, and the working time of spark plug is 30 ms. The experiments also got a high success rate of ignition.

Three piezoresistive pressure sensors, with the sensitivity of 0.5%FS, are used to measure the pressure inside the RDC (P_C), the hydrogen plenum (P_{H2}) and the air plenum (P_{Air}). The dynamic piezoelectric pressure sensors (PCB, 113B24), with the sensitivity of 10%, are installed on the outside wall of the RDC to measure the pressure trend of the RDW. The response time of piezoelectric transducer is lower than 1 μs, and the inherent frequency is more than 500 kHz. The location of sensors (p_1, p_2, p_3 &p_4) is shown in Fig. 1. Besides, a dynamic piezoelectric pressure sensor is mounted on the wall of air plenum, where closed to air-injection slot, to measure the high-frequency pressure wave which comes from combustor. An NI X Series multifunction data-acquisition device (DAQ) is used in the experiments for data acquisition. The data-acquisition card (USB-6366) based on NI-STC3 synchronization technology has eight channels of simultaneous analog input and a 16-bit ADC resolution. The single-channel sampling frequency is up to 2 MS/s, which is high enough to ensure the authenticity and stability of the pressure signal.

Experimental results and analysis

RDE operation process

Multiple experiments were carried out to verify the repeatability of results for every width of air-inlet slot. Three equivalence ratios ($\Phi = 0.88$, 1.08, 1.27) are used to study the effects on the stability of RDW. To ensure the air and hydrogen mass flow rate remains relatively stable before the operation of the RDC, the supply systems operate 0.8 s in advance of the RDC. The dynamic piezoelectric pressure sensor is unable to function for a long time in the experiment because of the high temperature in combustor; thus, the operation time of RDC is set at 0.4 s, which is controlled by the operation time of supply systems. Two sonic nozzles are respectively set at the manifold of the hydrogen and air supply system to control the mass flow rate of hydrogen and air. The air mass flow rate keeps constant value of 153 g/s in experiments, and the equivalence ratios are controlled by the hydrogen mass flow rate. Fig. 2a shows the static pressure curves during the operation of RDE. Fig. 2b shows the results of pressure wave which acquired via dynamic piezoelectric pressure sensors. The value of p_1 is obviously greater than other sensors, this is because the p_1 is located in the scope of detonation wave height, and others may close to the region of expansion.

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