Experimental demonstration of a multi-tube pulse detonation engine with a rotary valve

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1 Abstracts

Experimental demonstration of a pulse detonation engine (PDE) prototype, which incorporated with a rotary valve and multiple tubes, and utilized a mixture of kerosene and air, was described in this paper. Six detonation tubes of the PDE prototype with 60 mm equivalent diameter and 1000 mm length were arranged in a sector-annular configuration on a 219 mm diameter circle. The PDE was operated with a rotary valve and a gasdynamic valve to distribute the air and rich-fuel gas into the tubes respectively. The histories of gas pressure were measured to verify the regularity of detonation process in tubes. It was concluded that the PDE could operate in frequency 3×20Hz coordinately. Proof of the rotary-valved, multi-tube PDE operation was successfully demonstrated.

2 Introduction

Pulse detonation engines (PDEs) are unsteady propulsion devices that produce periodic thrust by utilizing repetitive detonation. They differ from conventional systems in two major ways: unsteady operation and detonative combustion. A typical operation cycle of a PDE includes four basic processes: initiation of detonation wave, propagation of detonation wave, exhausting of combustion products, and filling of reactants. In the last several decades, PDEs have attracted considerable attention because of their potential advantages in thermodynamic cycle efficiency, configuration simplicity, operation stability, and reliability[1,2].

PDE's potential performance advantage is related to its high operating frequency. In the case of multi-tube PDE, the operation coordination of all tubes is critical to the high working frequency, thus the investigation on the operation coordination of a multi-tube PDE has much significance [3]. In the multi-tube PDE, the coordination has two meanings: sequential detonation of the adjacent tubes and simultaneously detonation of the same group to generate similar pulse detonation wave. The coordination in the adjacent tubes may guarantee the quasi continuous thrust of the multi-tube PDE in the condition of low frequency of each tube. The different pulse detonation wave generated by the tubes in the same group may cause the torque acted on the rotary valve, thus preventing the rotation of the rotary valve and decreasing its operating life [4].

3 Experimental Setup and Procedures

The experimental setup includes a small combustor, a multi-tube PDE prototype, air and fuel supply system, ignition system, PCB pressure sensor, data collector, etc, The test system is shown in Figure 1.

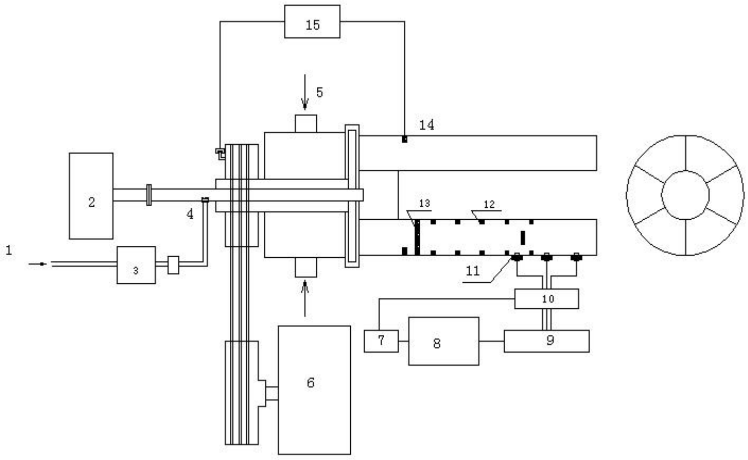


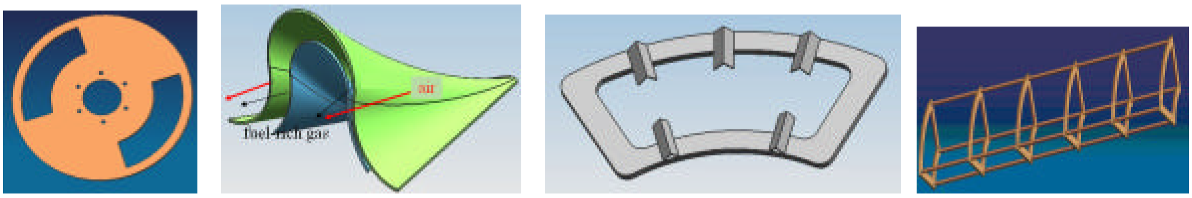
Figure 1. Schematic drawing of general experimental configuration (1.kerosene 2.small combustor 3.fuel pump 4.swirl injector 5.air inlet 6.drive electric motor 7.electrical source 8.CAS 9 A/D transducer 10.signal amplifier 11.pressure sensor 12.obstacles 13.disturbance apparatus 14.ignitor 15.controller)

In this test, aero kerosene is used as fuel, which is injected with a swirl injector into a center tube of PDE. Kerosene droplets are heated by hot combustion products expelled from a small combustor, then the oil vapor and droplets is mixed with the hot combustion products into an fuel-rich gas. Finally, the gas is discharged by six aero-valves into each detonation chambers. Fresh air, which is used as oxidizer and supplied by two roots blowers with total pressure 0.07MPa, is distributed into each detonation chamber by a rotary valve from a common air cavity, and mixed with the oil-rich gas ejected from the center tube of PDE into a detonable mixture.

The PDE prototype is combined with six detonation chambers, a center tube, a rotary valve, six aero-valves, a common air cavity with two inlets and other assistant elements. Each detonation chamber is a sector tube with 60mm equivalent diameter and 1000mm length, and the six detonation tubes are arranged in an annular configuration, seen in the figure 2, and every two symmetrical tubes are set in same group. The fillings of fresh air and hot fuel-rich gas are controlled by the rotary-valve and six aero-valves respectively. The rotary-valve is a disk with two symmetrical sector holes and a central hole. When the sector hole is align with detonation tube, fresh air will be filled to detonation tube from the common air cavity. The center hole of the dish valve is passage of the central tube of PDE. The states of each group of detonation chambers are controlled by the rotary-valve which rotation leads to sequential occurrence of air intake, detonation and exhausting in the tubes. The multi-tube configuration of PDE will guarantee the lasting thrust in the entire circuit, and not only enhance the average thrust but also decrease the flow drag. In addition, some assistant elements which may promote the generation of detonation wave, such as disturbance apparatus and obstacles, are applied in the chambers. Figure 3 shows the schematics of rotary-valve, aero-valves, and other assistant elements.

(a) (b)

Figure 2. Sector detonation tube configuration (a) and assembly configuration of six tubes (b)



(a) (b) (c) (d)

Figure 3. Diagram of rotary-valve disk (a), single-lobe aero-valve(b), disturbance apparatus(c) and obstacles(d)

The test of the PDE is conducted with two modes. At first mode, the hot fuel-rich gas is filled directly into the detonation tube from the center tube of PDE, as seen in the Figure 4. At the Second mode, shown in Figure 5, an isolator with a length of 300mm is added around the PDE center tube which is extended to the central position of detonation tube. The fuel-rich gas flows through the PDE center tube, then reversely flows into the isolator which has six ducts conjoint respectively to six aero-vales and detonation tube.

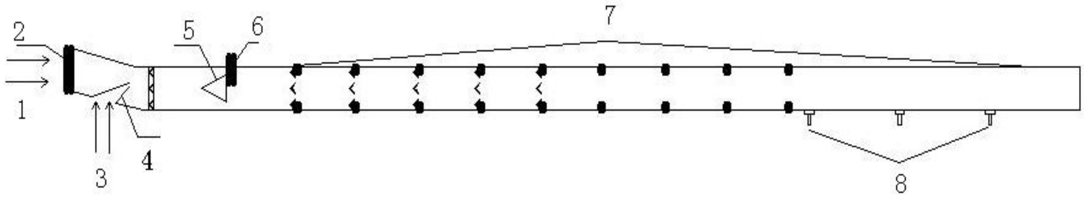


Figure 4. Diagram of experiment with no isolator (1.air 2 rotary-valve 3.fuel-rich gas 4. spring-lamination aero-valve 5.flame stabilizer 6.ignitor 7. disturbance apparatus and obstacles 8.pressure sensors)

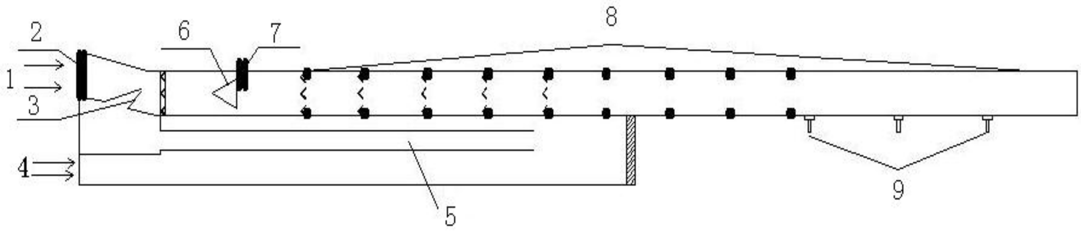


Figure 5. Diagram of experiment after installing the isolator (1.air 2.rotary-valve 3.single-lobe aero-valve 4.fuel-rich gas 5.isolator 6.flame stabilizer 7.ignitor 8.disturbance apparatus and obstacles 9.pressure sensors)

4 Results and Analysis

The investigation of the pulse detonation engine prototype is based on the adjusting of main air-flow pressure and fuel-rich gas temperature. The diagrams of the gas pressure sequence of the six detonation tube with different cases of operating are shown in Figure 6, Figure 7 and Figure 8. The sequence diagram of three adjacent tubes' superimposed pressure is shown in Figure 9.

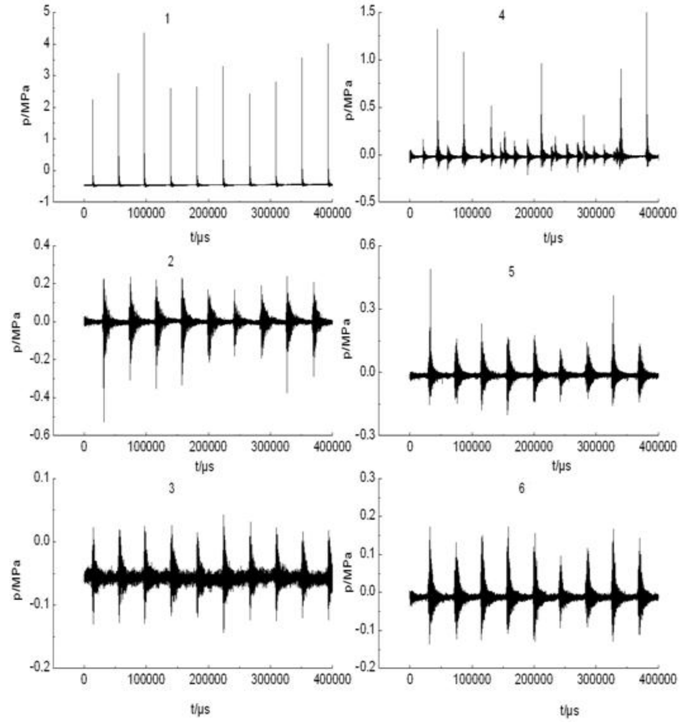


Figure 6. Pressure sequence diagrams of operating in the frequency of 22Hz, obtained from the PDE configuration without isolator

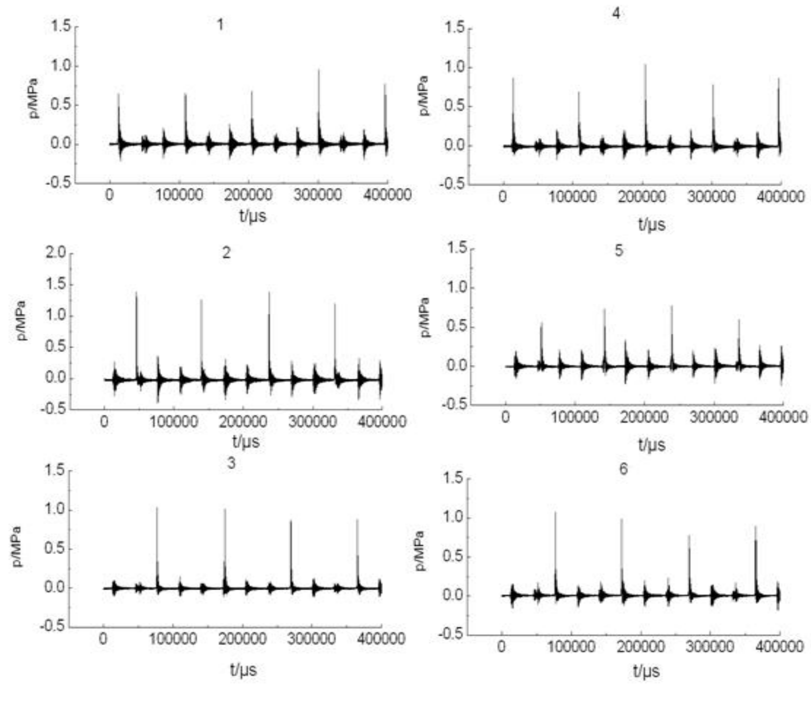


Figure 7. Pressure sequence diagrams of operating in the frequency of 10Hz, obtained from the PDE configuration with isolator

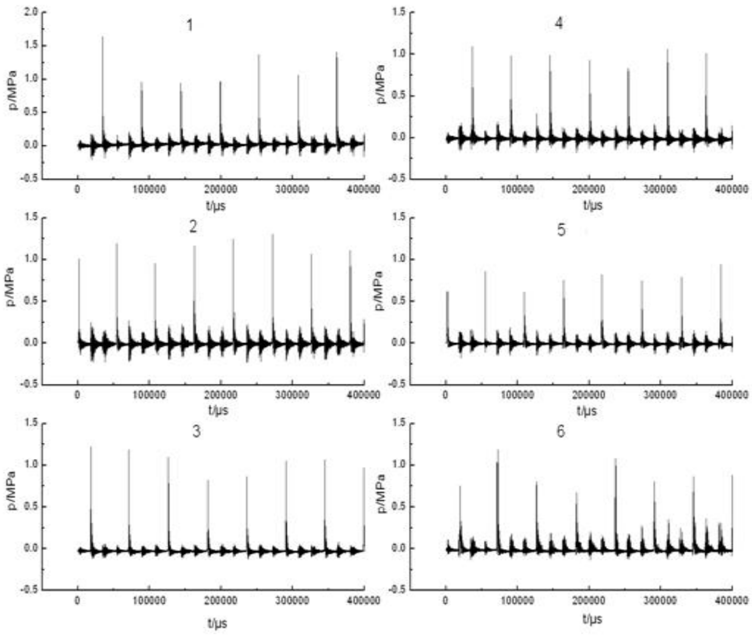


Figure 8. Pressure sequence diagrams of operating in the frequency of 20Hz, obtained from the PDE configuration with isolator

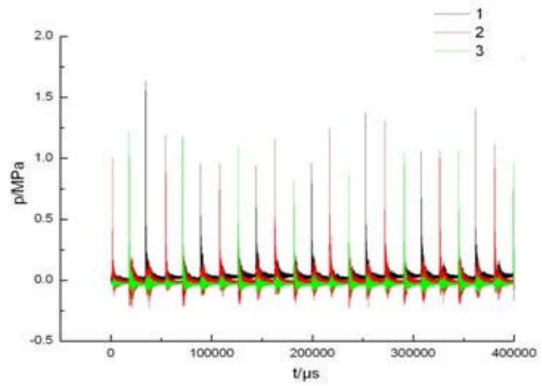


Figure 9. Superimposed pressure sequence diagrams of tube 1, 2, 3 of operating in the frequency of 20Hz, obtained from the PDE configuration with isolator

As shown in Figure 6, detonation was generated only in tube 1 and its pressure reached above 2.0MPa. The maximum pressure of gas in tube 4 which was opposite to tube 1 was 1.2MPa, but the pressures were unstable in different cycle. Other four tubes failed to detonate. We could conclude that every two symmetrical tubes and adjacent tubes did not coordinate with each other in this case. By contrast, the coordinating operations were obtained in two other cases, as shown in Figure 7 and Figure 8, although the pressures of detonations were lower than that of CJ detonation.

In the case of no isolator, the center tube of PDE serves as a shared oil chamber. Because all of lobe aero-valves connect with the shared oil chamber, the combustion product generated from detonation would return to the shared chamber. The backflow of the product, on one hand, contaminates severely the fuel-rich gas in the shared chamber. On the other hand, it causes the high pressure of the shared chamber that exerts a negative effect on the filling process of fuel leading to the failure of ignition or DDT. It shows that the backflow caused by the detonation of tube 1 could affect the filling process in tube 2 and tube 3 as seen in the Figure 6. After the installation of the isolator, product of detonation has to pass through isolator duct before entering the shared chamber. If the isolator were long enough, the product would return to detonation chambers without polluting fuel and affecting the filling process of the adjacent chambers. The isolator leads to a relative independence of each tube and prolong the distance before the fuel entering the chambers, in other words, it increases the fuel evaporation time and guarantees enough high evaporation rate. Based on observation above, the isolator benefits the coordination of multi-tube PDE, as shown in the Figure 7 and Figure8.

In this experiment, the inner side of detonation tube was used to heat fuel. As frequency increased, the heat release rate of the inner side of tubes increases, which leads to the enhancement of fuel evaporation rate. As the increase of evaporation rate, the pressure of inner tuber increases such that enhances the penetration of fuel and decreases the distribution differences of each tube. As a result of effects above, the adjacent tubes detonates in sequence with similar pressure characteristics. In addition, shown in Figure 7 and Figure 8, as the increase of frequency, the increased intensity of detonation wave in each tube attributes to the homogenizing of the mixture.

As the increase of frequency, the upper limit of detonation equivalent ratio increases while the lower limit decreases [5]. Synchronous detonation requires similar fuel distribution and concentration in each tube. So the well-designed lobe aero-valves with same structure are required.

5 Conclusions

A PDE prototype consisting of six combustors was designed and built. Six detonation tubes were arranged in an annular configuration on a diameter 219 mm. circle. Each tube was 60 mm equivalent diameter with a length of 1000 mm. Multiple-cycle detonations with maximum frequency 3× 20Hz were achieved successfully. The resuits from this experiment have suggested the following conclusions.

1) The backflow of combustion product could contaminate the shared oil chamber. After the installation of isolator, the product entered into isolator instead of shared oil chamber, and then returned to detonation tubes at the beginning of the next cycle of air intake, thus providing the synchronous detonation and ensuring that the adjacent tubes detonates in sequence.

2) After the installation of isolator, the high temperature of inner wall would heat the fuel and increase evaporation rate of fuel.

3) The intensity of detonation wave increases as the increasing of frequency.

References

[1] M.A.Mawid and T.W.Park. Towards Replacement of Turbofan Engines Afterburners with Pulse Detonation Devices. AIAA 2001-3470,July 2001.

[2] Yan Chuanjun, Fan Wei, Theory and Key Technologies of Pulse Detonation Engine, Press of Northwestern Polytechnical University: P225－268

[3] Han Qixang,Study on Detonation Theory and a Rotary-Valved Pulse Detonation Engine Prototype:[Thesis of Doctor Degree]. Nanjing University of Aeronautics and Astronautics, 2004

[4] Li Shenpeic Investigation of Key Technologies on A Pulse Detonation-turbofan Engine Controlled by Rotary Valve: [Thesis of Master Degree]. Nanjing University of Aeronautics and Astronautics,2009

[5] Huang Xiqiao,Yan Chuanjun, Experimental Investigation of Effects of Detonation Frequency on Performance of Pulse Detonation Engine， Journal of Northwestern Polytechnical University, VOl 25,No 1,Feb,2007, p22-27.