Experimental investigation on the coal powder rotating detonation engine

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1 Introduction

Compared with the constant pressure combustion, the detonation process is close to constant volume combustion and has higher thermal cycle efficiency. Coupled with the advantages of simple structure and large specific impulse of detonation combustion chamber, detonation engine has been favored by researchers in recent decades. At present, the detonation engines around the world mainly include pulse detonation engine (PDE) [1,2], rotating detonation engine (RDE) [2-4] and oblique detonation engine (ODE) [2,5,6]. The physical states of fuels used in detonation propulsion include gaseous, liquid and solid, and gaseous and liquid fuels are the main fuels.

Recently, the engineering application of PDE is limited due to its intermittence and periodicity of operation, high-frequency and high-energy initiations, and tremendous energy loss. And the strict requirement of ODE on incoming flow state prevents the development of relevant research. In contrast, RDE is favored by many researchers because of its many advantages such as, one-time initiation, 'continuous' mode operation, step increase in efficiency, self-sustaining and self-compression of detonation waves, large effective thrust at a low-pressure ratio, a wide range of inflow velocity, and design simplicity [3,4].

Powder not only has the advantages of adjustable flow and high combustion efficiency like liquid fuel, but also has the advantages of high calorific value, high density and easy storage like solid fuel [9,10]. In recent years, researchers have done a lot of research on the detonation characteristics of powder [7], but the formal application of powder fuel in detonation engine is still in initial research stage. At present, Bykovskii et al. [8-10] from Russia have conducted relevant research on the rotating detonation process of pulverized coal in a disc combustion chamber, but they did not accurately and stably control the fuel flow in the experimental process. Dunn et al. [11,12] from the United States conducted a preliminary experimental investigation on the rotating detonation of pulverized coal in an annular combustor in 2021.

In this study, hydrogen is used to fluidize the pulverized coal sent to the fluidizing chamber at a certain speed and bring it into the disc combustion chamber to fully mix with the air. Then the ignition test of powder rotating detonation engine was carried out by using hot jet. Furthermore, the detonation characteristics of different particle sizes of porous anthracite and the differences of relevant parameters between micron porous anthracite (PA) and flake anthracite (FA) are compared. This work can be used as an important reference for the subsequent test of powder continuous rotating detonation engine and the new utilization of coal.

2 Experimental Setup

The experimental system is shown in Figure 1. The system mainly includes disc test engine, gas supply system, powder supply and fluidization system, ignition system, control and data acquisition system, etc. Each gas pipeline is equipped with a gas flowmeter to monitor the gas flow in real time. The diameter of the disc combustion chamber is 150mm and the outlet diameter is 50mm. Figure 2 shows the ignition position of the combustion chamber and the position distribution of the high-frequency pressure sensor used in the experiment. Where r_1 = 40 mm, r_2 = 67 mm, r_3 = 55 mm. The circumferential coordinates of PCB3 and PCB4 are defined as 0, PCB1 and PCB2 are at 90 °. Accordingly, the circumferential coordinate of the ignition is 180 °.

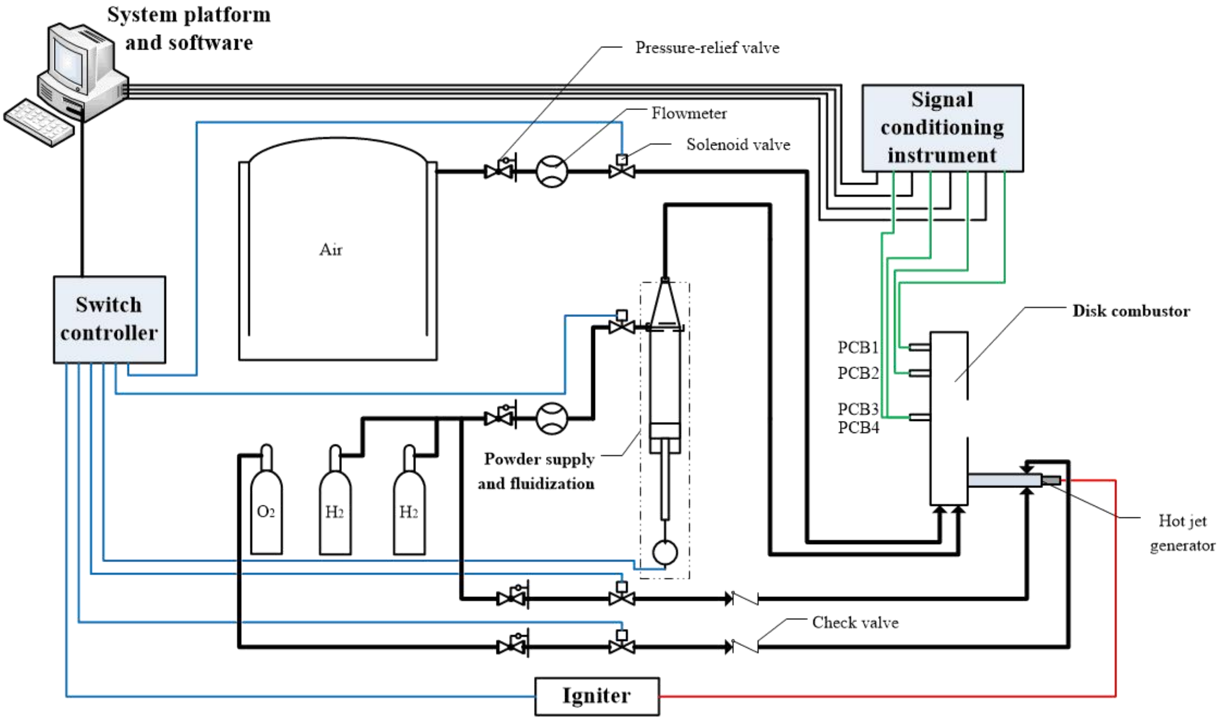

Figure 1. Experimental system

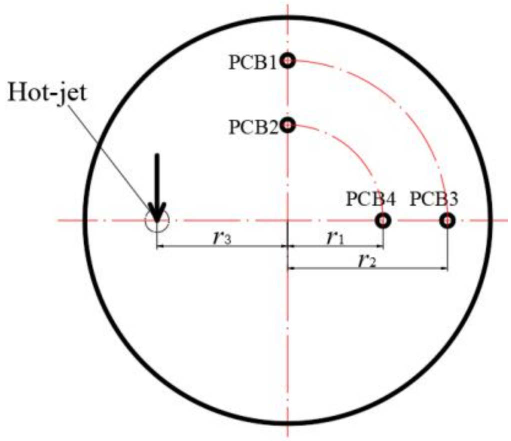

Figure 2. Ignition position and sensor arrangement inside the combustion chamber

Figure 3 shows the experimental control sequence. The arrows on the upper and lower sides represent the opening and closing of the project respectively. To protect the sensors and test machine, the continuous running time of the engine is $\Delta t = 650$ ms.

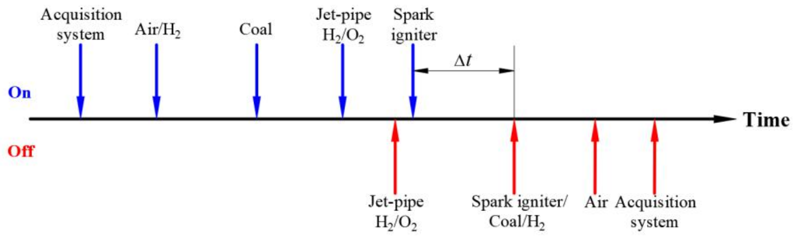

Figure 3: Experimental control sequence

3 Results and Discussion

To explore the effects of pulverized coal particle size and morphology on rotating detonation wave, 11 cases are designed on the condition of air flow of 260 g/s, as shown in Table 1. Each case in the study corresponds to more than two ignition tests.

Table 1. Information of test conditions

Case	Fuel	Oxidant	Equivalence ratio (ER)		
			H_2	Coal	Total
1	H_2	Air	0.7	0.0	0.7
2	H_2 + porous anthracite (20nm)		0.7	0.3	1.0
3			0.7	1.0	1.7
4	H_2 + porous anthracite (50nm)		0.7	0.3	1.0
5			0.7	1.0	1.7
6	H_2 + porous anthracite (3μm)		0.7	0.3	1.0
7			0.7	1.0	1.7
8	H_2 + porous anthracite (40μm)		0.7	0.3	1.0
9			0.7	1.0	1.7
10	H_2 + flake anthracite (5μm)		0.7	0.3	1.0
11			0.7	1.0	1.7

Figures 4 and 5 show the results of a test in Case 4. It can be seen that in the initial stage of the formation of rotating detonation wave, the detonation pressure in the combustion chamber is high. With the continuous detonation, the pressure peak measured by the sensors gradually decreases and tends to be stable. After the fuel supply is cut off, the high-frequency pressure peak rises in the last stage of detonation after a period of decline. In the whole process, the pressure difference of fuel or air injection hole is quite consistent with it. It is proved that the detonation pressure is positively related to the amount of fuel supply during the rotating detonation of hydrogen / coal / air in a disk combustion chamber.

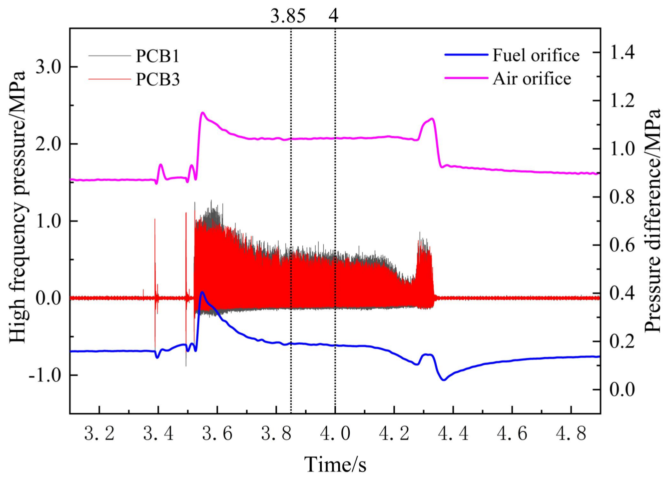

Figure 4. High frequency dynamic pressure of combustion chamber and pressure difference of orifices

Figure 5 shows the high frequency pressure profiles of the test between 3.8565 s and 3.8595 s. Obviously, the measured pressures of PCB1 and PCB3 (PCB2 and PCB4) with the same radial position are basically the same. And the time period Δt_1 is about 4 times larger than Δt_2, which indicates that the detonation wave in the combustion chamber propagates stably in a counterclockwise direction.

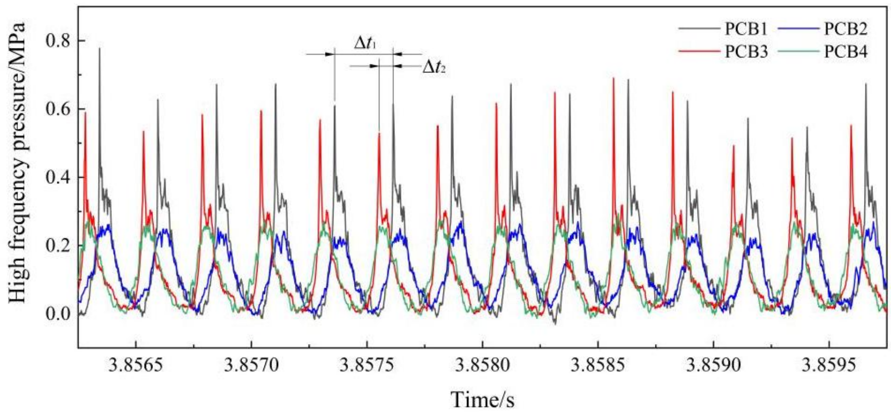

Figure 5. High frequency pressure profiles at test points when rotating detonation is stable

Figures 6 and 7 show the distribution of peak pressure and detonation frequency measured by PCB1 in multiple tests, as well as the mean value of test results under the same working conditions. As shown in Figures 6 and 7, the peak pressure (base pressure) measured by PCB1 during pure hydrogen detonation is 0.61 MPa, and the dominant frequency (base dominant frequency) of detonation wave propagation is 3882 Hz. For porous anthracite powder of each particle size, when the total equivalence ratio is 1.0, the peak pressure measured by PCB1 in each test is higher than the base pressure, and the dominant frequency of detonation wave propagation is higher than the base dominant frequency. When the total equivalence ratio is 1.7, the peak pressure measured by PCB1 is higher than the peak pressure on the corresponding working condition with equivalence ratio of 1.0, but most test results of the dominant frequency of detonation wave propagation are lower than the base dominant frequency.

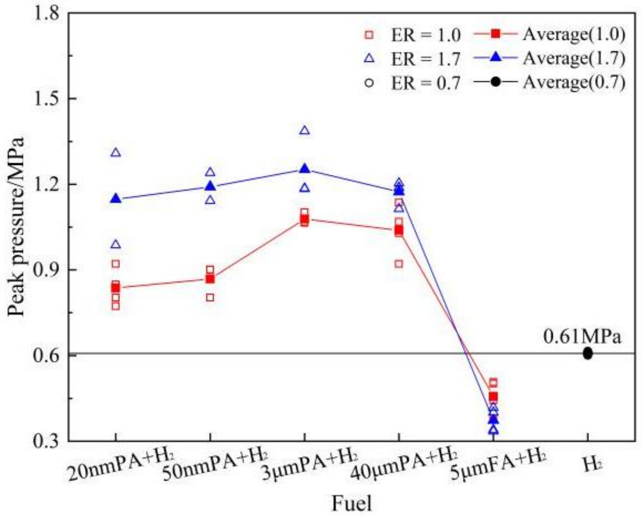

Figure 6. Average peak pressure of PCB1 in the tests

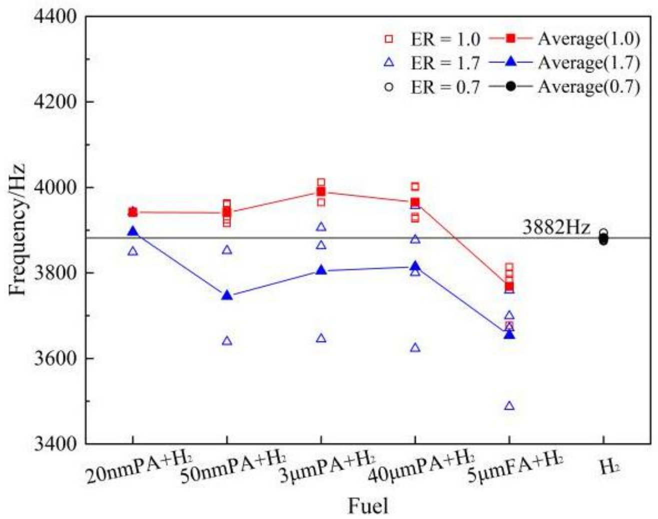

Figure 7. The dominant frequency of detonation wave propagation in the tests

From the average results of the pressure peak and the dominant frequency of detonation wave propagation in each case, it can be seen that when the total equivalence ratio is 1.0, the detonation performance of 3μm porous anthracite powder is the best among the kinds of porous anthracite powder used in the experiment. And the peak pressure and dominant frequency of the detonation wave in Case 6 are 1.08 MPa and 3990 Hz respectively.

In the ignition tests of the flake anthracite powder, the peak pressure and detonation wave propagation frequency measured by PCB1 are lower than the corresponding parameter values of 3 μm and 40 μm pulverized porous anthracite. The higher the flow rate of the flake anthracite powder, the lower the pressure peak and detonation wave propagation frequency measured by PCB1.

4 Conclusions

Based on the accurate control of flow rate, the stable rotating detonations of different sizes of porous anthracite powder and micron flake anthracite powder were realized in this study. In the initial stage of rotating detonation wave formation, the detonation pressure in the combustion chamber is high, and then with the continuous detonation, the detonation pressure gradually decreases and tends to be stable.

The experimental results showed that when the hydrogen flow is constant and the hydrogen-air equivalence ratio is 0.7, the detonation pressure can be increased by adding porous anthracite powder to hydrogen. And the detonation pressure with a total equivalence ratio of 1.7 is higher than that with a total equivalence ratio of 1.0. At the same time, adding a small amount of porous anthracite to hydrogen can improve the propagation frequency of detonation wave. However, the addition of a large amount of porous anthracite reduces the propagation frequency of detonation wave. When the total equivalence ratio is 1.0, 3μm porous anthracite powder has the best detonation performance among the 4 kinds of porous anthracite powder. Compared with porous anthracite powder, the detonation performance of flake anthracite powder with the same particle size of micron is not ideal.

5 Acknowledgement

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