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Experimental Study of the Propagation Characteristics of Heated Air-Ethylene Rotating Detonation Wave in a Hollow Combustor

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Abstract

This experimental study discusses the propagation characteristics of rotating detonation waves (RDWs) in a hollow rotating detonation combustor (HRDC) using heated air-ethylene as the working fluid. Through the combination of high-frequency pressure data and high-speed photographic images, a detailed analysis of RDW propagation under high-temperature incoming flow is conducted. Additionally, the effect of equivalence ratio on RDW stability is investigated. Stabilized RDWs were successfully achieved in the experiment at a maximum total air temperature of 711 K. For total air temperatures below 650 K, a wide range of injection equivalence ratios (1.0-1.3) allows for the attainment of stable single-wave modes. Experimental results demonstrate that under high-temperature incoming flow conditions, RDWs exhibit a significant peak pressure drop while experiencing minimal velocity loss. The color of the RDWs appears lighter and a noticeable deflagration glowing area is observed within the combustion chamber. Various modes of unstable propagation are observed in RDWs, including the coexistence of single-wave and deflagration modes, the coexistence of doublel waves and deflagration modes, as well as rapid switching between single and double waves. In a HRDC , the existence of a central reflow zone along with a substantial amount of deflagration causes fuel loss, resulting in the RDW front equivalence ratio that is frequently lower than the injection equivalence ratio. The stable single-wave mode is primarily achieved under fuel-rich conditions. As the temperature of the air increases, a higher equivalence ratio is required to obtain a stable single-wave mode, and the range of equivalence ratios becomes narrower.

Keywords: *Rotating detonation wave; Hollow combustor; Propagation characteristics; Air-Ethylene; Flow field.*

1. Experimental setup

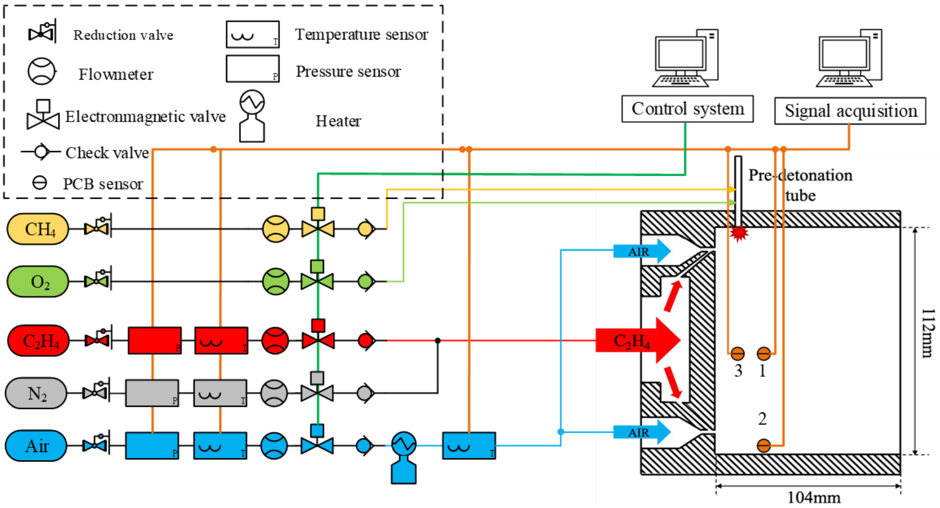

Fig 1. Schematic diagram of the experimental system

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The experimental setup for the rotating detonation of heated air-ethylene includes several components, namely, propellant supply systems, a heater system, a fuel supply system, a rotating detonation combustion chamber, an ignition system, and a control and data acquisition system. These components are illustrated in Fig. 1.

2. Results and discussion

Within the mass flow rate range of 160-250g/s, a consistent supply of hot air is maintained. The total temperatures range from 556K to 711K, with an equivalence ratio between 0.84 and 1.46. Through a series of comprehensive experiments, the approximate operating range of heated air-ethylene rotating detonation in a HRDC has been determined. Several representative experimental conditions were chosen for detailed analysis, and the corresponding results are presented in Fig. 2.

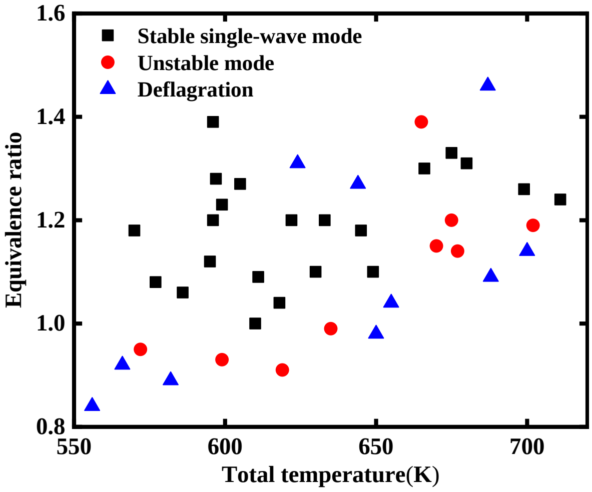

Fig2. Schematic diagram of experimental working condition results

3. Characterization of steady detonation wave propagation

Based on the experimental findings presented in Fig. 2, the combustion chamber demonstrated a broad range of equivalence ratio conditions (1.0-1.3) at total air temperatures below 650 K. These conditions enabled the stable operation of single-wave modes, with the majority of them are fuel-rich mixtures. For detailed analysis, several representative conditions were selected, as illustrated in Fig. 3. Stable single-wave modes were obtained at a total inlet temperature of 650 K and an equivalence ratio of 1.22. The pressure curves recorded by PCB1 during 300ms of stable engine operation, along with high-speed photographic images capturing one cycle of detonation wave propagation, are presented. To mitigate the impact of temperature drift, high-pass filtering was applied to the PCB voltage signals, followed by conversion to pressure values. In order to facilitate comparative analysis, a room temperature test was conducted (Fig. 4), featuring a total inlet temperature of 350 K and an equivalence ratio of 1.21. The pressure curves and FFT frequency distributions of both tests are displayed in Fig. 5.

Upon analyzing the localized enlargement of the pressure curve in Fig. 3, it can be observed that the peak pressure of the detonation wave is approximately 0.4 MPa, with some fluctuations in the pressure at the wave head. The main frequency (f) of the detonation wave in the high-temperature incoming flow is measured to be 5113 Hz. The diameter of the combustion chamber (Dc) is 112 mm. By applying Eq. (1), the propagation velocity (v) of the detonation wave can be calculated as 1800 m/s. Comparing this with the theoretical detonation velocity of C-J (1843 m/s), the velocity difference is approximately 2.3%.

$$v = f \pi D_C \tag{1}$$

Similarly, upon examining the localized enlargement of the pressure curve in Fig. 4, it is evident that the peak pressure of the detonation wave is approximately 1.2 MPa, with a more stable pressure at the wave head. The main frequency (f) of the detonation wave at room temperature, shown in Fig. 5, is recorded as 5170 Hz. From this, the calculated detonation wave velocity (v) is estimated to be 1820 m/s. Comparing it to the theoretical detonation velocity of C-J (1864 m/s), a difference in velocity of around 2.4% is observed. The comparison reveals that as the air temperature increases, the intensity of the detonation wave noticeably decreases, aligning with the principles stated in the C-J theory. According to the C-J theory, the increase in the temperature of the working mass will slightly reduce the propagation speed of the detonation wave. This experimental result confirms the theoretical predictions. It is worth noting that in the experiments, the pressure of the air gas source was kept constant. When the air is heated, the mass flow rate decreases due to the thermal resistance effect. The decrease in mass flow rate could potentially affect the propagation modes of the detonation wave . In Fig.s 3 and 4, the mass flow rates were 178 g/s and 248 g/s, respectively. However, the air-collecting chamber pressure is higher under the high-temperature incoming flow. Throughout the experiments, we maintained a constant upstream air pressure, without deliberately eliminating the impact of heating on mass flow rate variations. Meanwhile, in section 3.3, several working conditions with a constant flow rate were selected for comparative analysis.

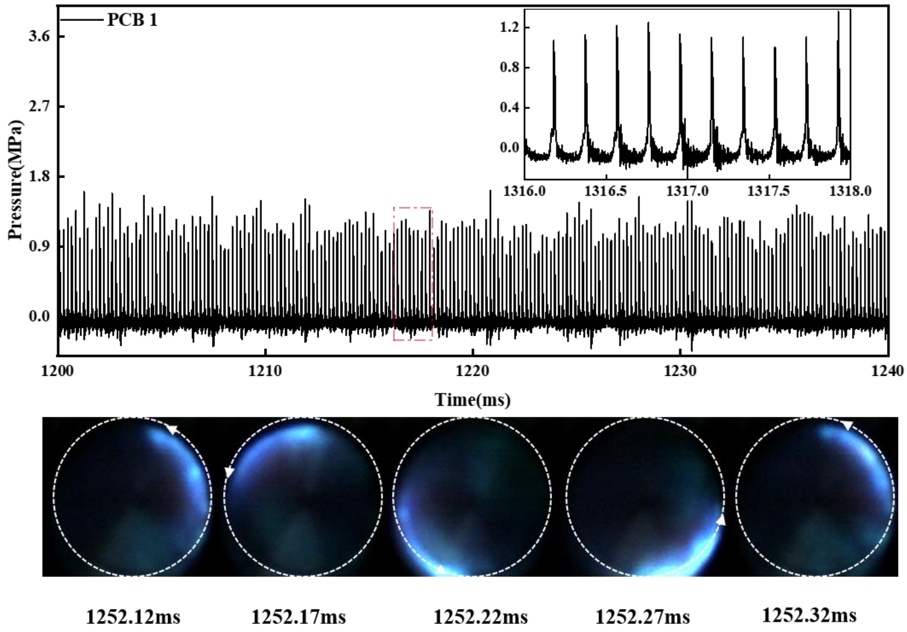

Fig3. Inlet total temperature of 650K, equivalence ratio of 1.22 pressure curve and combustion chamber operating diagram

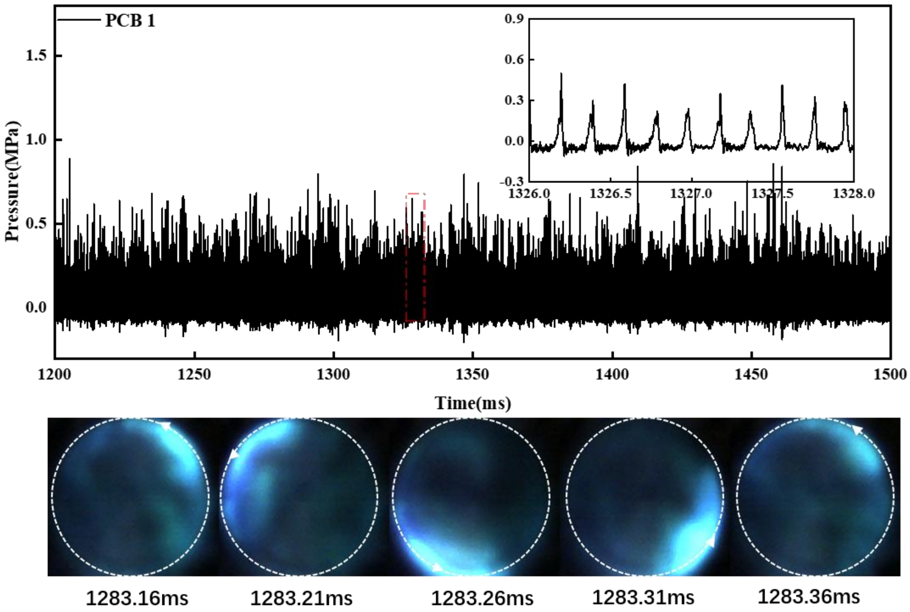

Fig4. Inlet total temperature of 350K, equivalence ratio of 1.21 pressure curve and combustion chamber operating diagram

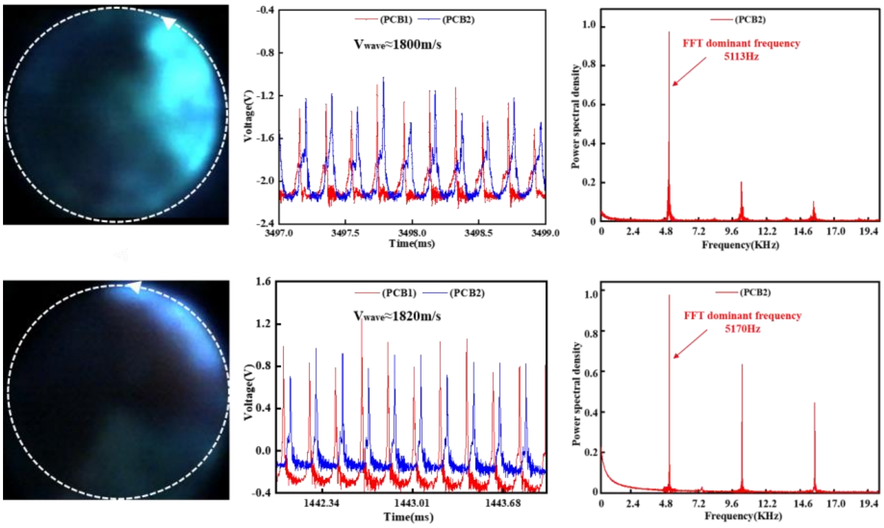

Fig5. Comparison of detonation wave characteristics at room temperature and under heating conditions

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