The effect of Cavity Location on Continuous Rotating Detonation Wave fueled by ethylene-air

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1 Introduction

With the advantages of pressure gain and high thermodynamic efficiency, detonation combustion is an efficient and promising combustion mode. For aerospace propulsion, Continuous Rotating Detonation (CRD) Engine has been considered as a feasible and attractive application, as it can produce stable thrust with simple combustor structure and effortless ignition [1]. For engineering application, hydrocarbon fuel is still ideal propellant for CRD Engine in consideration of safety and cost. However, the CRD fueled by hydrocarbon fuel still faces the realization and stable operation problem in the annular combustor [2, 3]. Without the additional hydrogen or oxygen to improve the propellant chemical activity, the hydrocarbon-air CRD wave failed [2] or propagated approximately in sound speed [3], namely, degenerated into quasi-detonation [4]. For hydrocarbon fuel, mix and heat release require longer axial distance and residence time. The operation mechanism of hydrocarbon CRD is still not clear, which is urgent to be studied further.

In the hollow chamber combustor, methane-oxygen CRD [5] and hydrogen-air CRD [6] have been verified experimentally. It is worth noting that ethylene-air CRDs also have been accomplished with little velocity deficit and large operating range [7, 8]. The flame stabilization in re-circulation zone and wider combustor are key factors for the remarkable and stable operation of ethylene-air CRD [7]. It is indicated that the hydrocarbon fuel CRD also can be achieved excellently using the appropriate approaches. For the scramjet, the ignition and flame stabilization in the supersonic inflow are difficult. The cavity structure has been widely studied and employed for flame stabilization as well as promoting mixing quality [9]. The flame stabilized in the cavity can operate as pilot flame. Inspired by the cavity flameholder and hollow chamber, the annular combustor with the cavity structure in the inner body has been proposed.

Since the cavity structure is considered as an effective improvement approach for hydrocarbon CRD, the location of the cavity is a problem deserving to be studied. In the scramjet, the relative location of cavity flameholder and fuel injection ports is a significant factor for promoting mixing quality and flame stabilization. Based on it, the fuel injection can be categorized into three types: far-field injection, near-field injection and cavity injection, which will influence cavity combustion stabilization mode. This paper mainly focuses on the effect of cavity location on CRD fueled by ethylene-air. Series of experiments have been conducted with the variation of cavity arrangement. Through the optical observations, high-frequency

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pressure and absolute pressure measure, the flame distribution and propagation characteristics of ethylene-air CRD have been discussed.

2 Experimental System

Designed for flame stabilization, an annular combustor with the cavity in the inner cylinder is proposed, as shown in Fig.1. The external diameter of original annular combustor is 130 mm with the combustor width of 15 mm. An annular cavity with the aft wall angle of 45 degree is arranged in the inner body. The cavity depth is 20 mm, and its length-to-depth ratio is 5.5. The axial distance from the cavity upstream leading edge to the combustor inlet is defined as L_c. Four cavity arrangements are adopted, namely, L_c=0, 20, 40, 60 mm, denoted as combustor A, B, C and D, respectively. The combustor length is 190 mm, and the combustion products are discharged into the atmosphere through the nozzle. A hot tube connected tangentially to the combustor is applied for the detonation ignition.

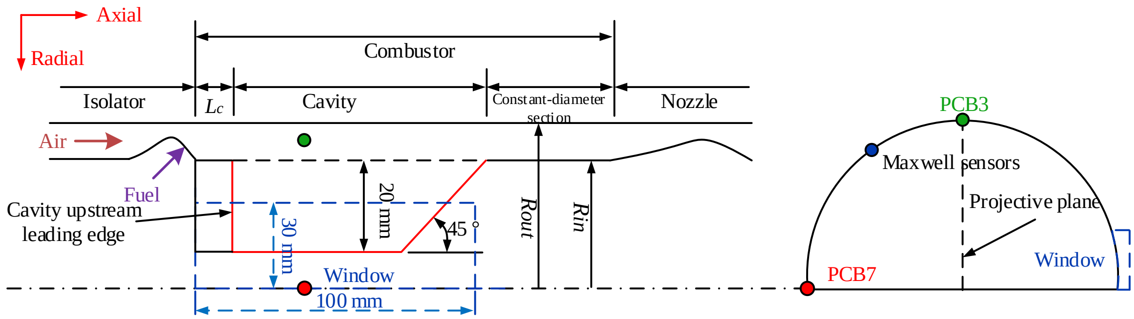

Fig.1 Schematic diagram of the annular combustor with cavity

The high-frequency pressure measure and absolute pressure measure are implemented in the experiment. Their measure arrangements are marked in Fig.1. The piezoelectric sensors (Model: PCB113B24) are adopted in the high-frequency pressure measure system with the measure frequency of 2 MHz. The piezo-resistance sensors (Maxwell, Model MPM480) are used for axial absolute pressure distribution measure. The acquisition frequency is 500 Hz with measure error of 0.5% full scale. In addition, the Photron Fast Camera SA-X is used for the optical observation. In the projective plane, the projection of the observation window is a rectangle, which is 60 mm in height and 100 mm in length, as illustrated in Fig.1. The sequential high-speed photography images are obtained at the frame rate of 45 kHz with the resolution of 512 × 640 pixels. And its exposure time is 1/65842 s.

3 Results and analysis

Keeping the mass flow rate of air in the range of 730-750 g/s, series of experiments have been performed with the alteration of cavity arrangement and equivalence ratio (ER). The operating range and frequency distribution of CRD fueled by ethylene-air in four combustor schemes are summarized, as shown in Fig.2. Two-waves in homo-rotating mode and two-waves in hetero-rotating mode have been found, marked as '▲' and '▼', respectively. The failure operating condition means that CRD cannot be ignited or extinguish during the test, marked as 'X'. In combustor A and B, CRD waves propagate in two-waves in homo-rotating mode. Their lean limit ERs are approximately 0.70. Once the cavity is arranged downstream, CRD waves will propagate in two-waves in hetero-rotating mode with smaller operating range, just like in the original annular combustor. The propagation frequency in combustor B is the highest among the four combustor.

When ER is 1.02, the propagation velocity is 1234.81 m/s accounting for 67.5% of corresponding CJ velocity, which evidently exceeds other ethylene-air CRD research results in annular combustor.

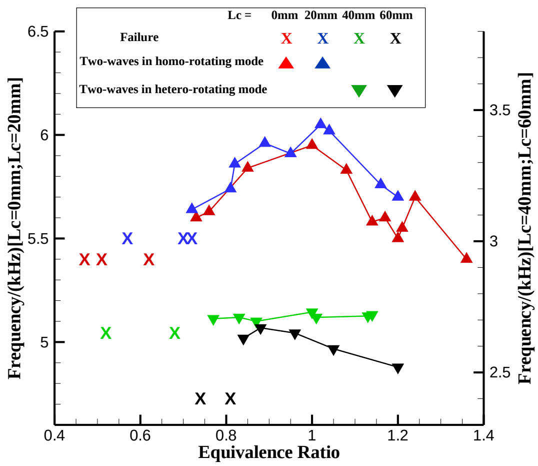

Fig.2 Frequency distribution

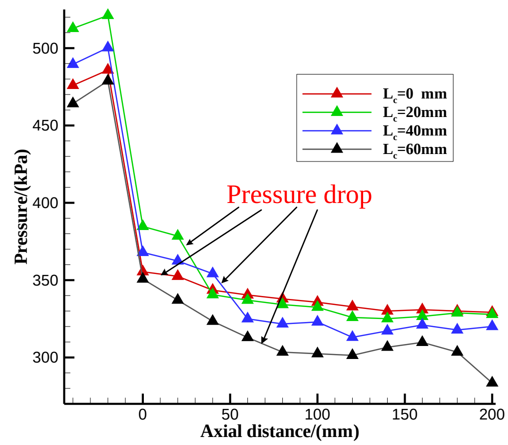

Fig.3 Axial pressure distribution

In order to figure out the effect of cavity location on CRD wave in detail, the typical cases around stoichiometric ER are chosen. Their experimental conditions are listed in Table 1.

Table.1 The typical experimental conditions

Test	Combustor location	$\dot{m}_{air}(g/s)$	ER	Propagation mode	f (kHz)
#1	L_c = 0mm	743	1.00	Two-waves in homo-rotating mode	6.02
#2	L_c=20mm	740	1.02	Two-waves in homo-rotating mode	6.05
#3	L_c=40mm	745	1.00	Two-waves in hetero-rotating mode	2.73
#4	L_c=60mm	738	0.96	Two-waves in hetero-rotating mode	2.65

Fig.3 shows the axial pressure distribution of Test #1-#4. Owing to the sudden enlargement area in the cavity forepart, there will be a pressure drop in the axial pressure distribution. In combustor A, the pressure drop is minor, due to the heat release and pressure increase of CRD waves self-sustaining around the combustor inlet. For combustor B- D, the pressure drops are distinct and the pressure drop location moves downstream with the cavity moving downstream. The outlet pressure and isolator pressure of combustor A and B are higher than that of combustor C and D. It is indicated that the detonation combustion intensity is higher in combustor A and B.

Fig.4- 7 show the flame distribution and propagation process of Test #1- #4, respectively. The flame move tracks are clear and distinguished. The CRD waves propagate as homo-rotating mode in combustor A, B and propagate as hetero-rotating mode in combustor C, D. In all combustors, the CRD wave flame can self-sustain around the combustor inlet. It is clear that the flame luminance in re-circulation zone gradually decreases with the cavity moving downstream. In combustor A and B, there are distinct flame distribution in the re-circulation zone. And the CRD wave flame and re-circulation zone flame are an integration. With the support of pilot flame in the wave front area, CRD waves propagate as homo-rotating mode. However, there are obvious gaps between CRD wave flame and re-circulation zone flame in combustor C and D. Without the support of flame stabilization in wave front area, CRD waves propagate as hetero-rotating mode to accelerate heat release for self-sustaining. Fuel has been consumed and the cavity effect weakens.

The detonation cell size of stoichiometric ethylene-air under normal temperature and atmospheric pressure is about 26 mm. Combined with the operating range, axial pressure distribution and flame distribution, the cavity provides maximal effect to CRD propagation, when L_c is smaller than cell size, namely, the cavity is approximately arranged in CRD wave front area.

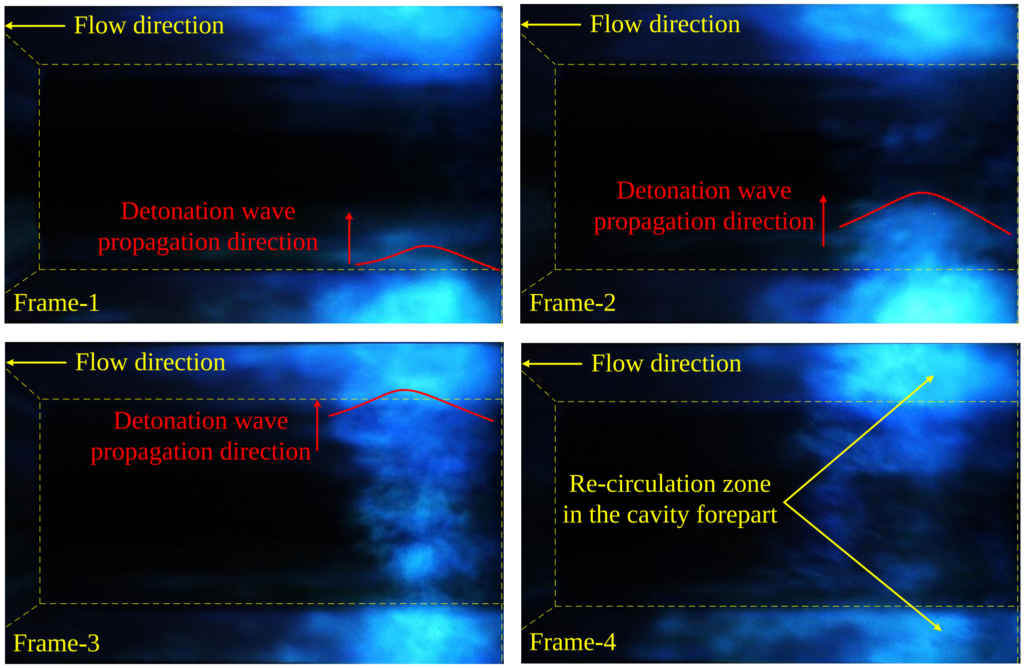

Fig.4 High-speed photography images of two-waves in homo-rotating mode in Test #1

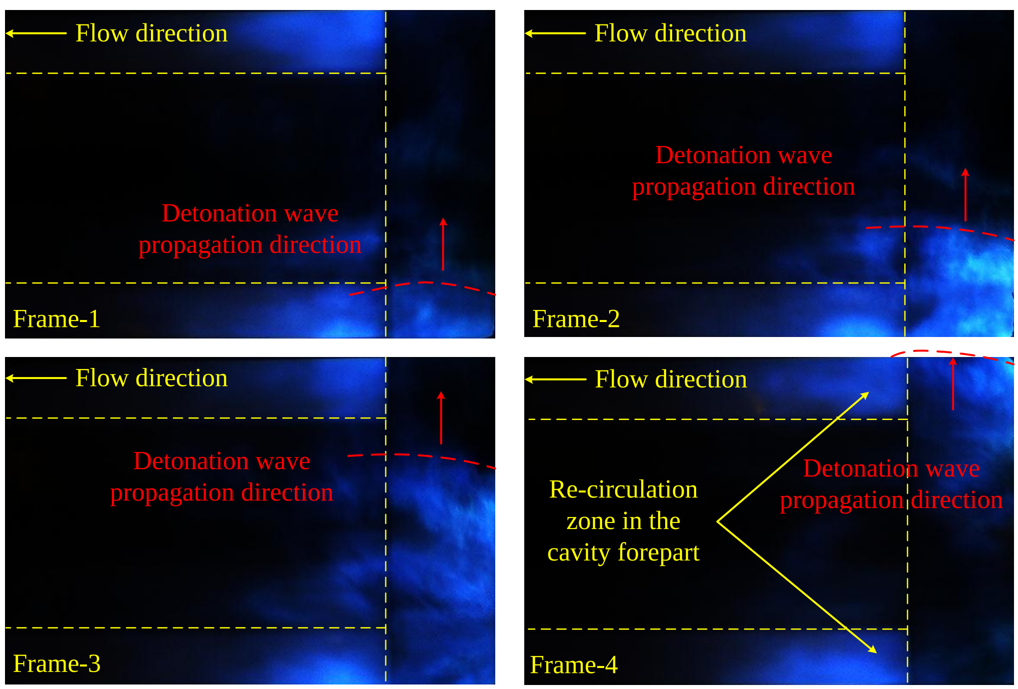

Fig.5 High-speed photography images of two-waves in homo-rotating mode in Test #2

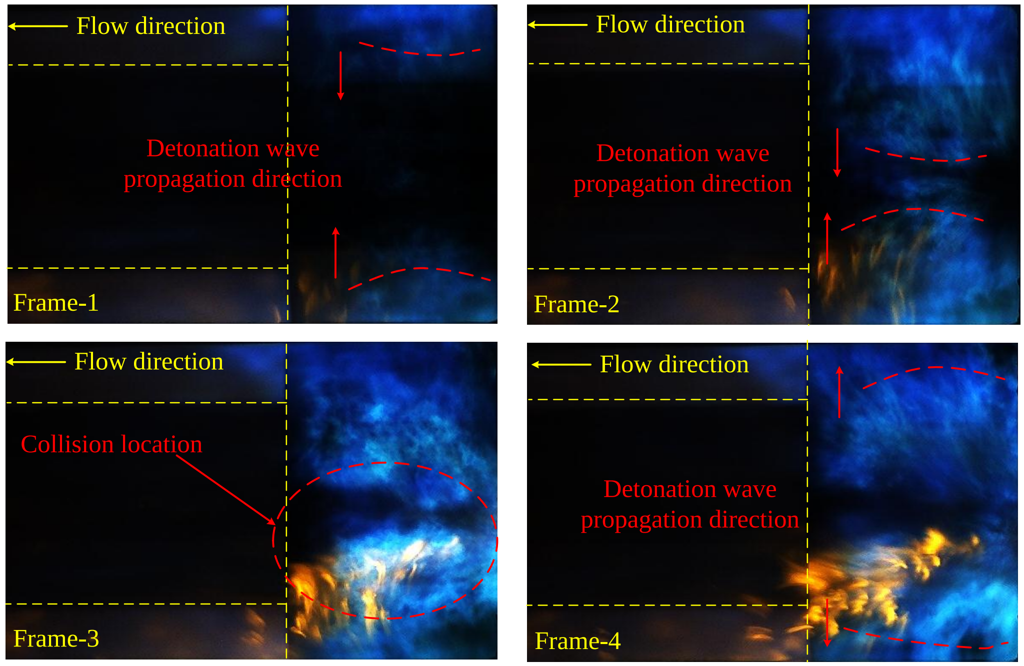

Fig.6 High-speed photography images of two-waves in hetero-rotating mode in Test #3

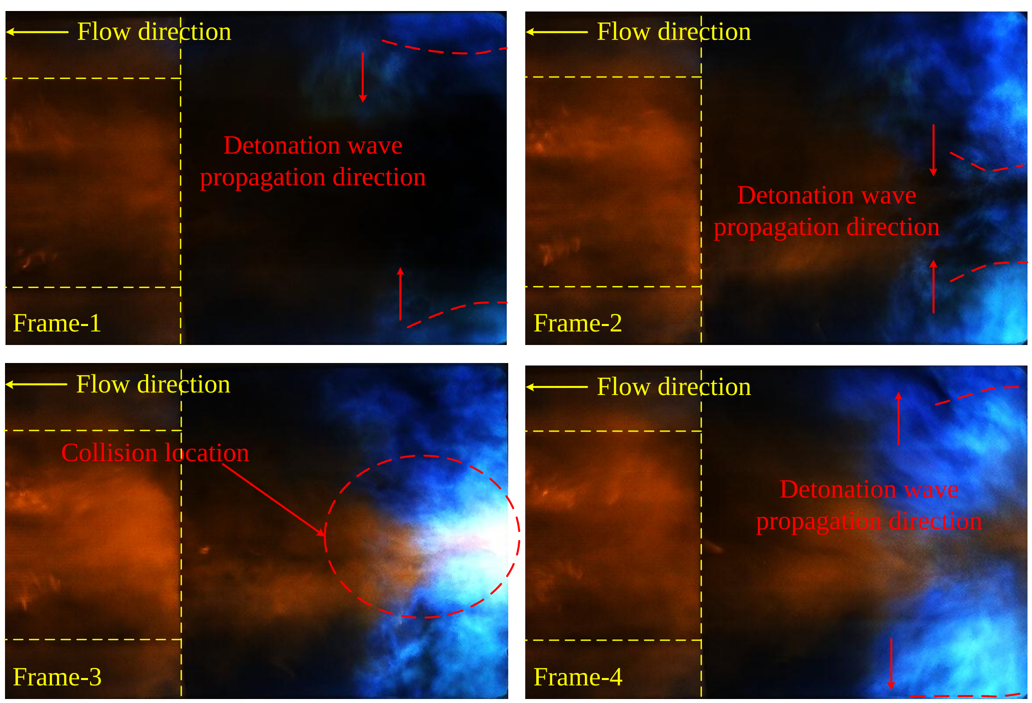

Fig.7 High-speed photography images of two-waves in hetero-rotating mode in Test #4

4 Conclusions

Ethylene-air CRD has been achieved in the annular combustor with cavity. The flame stabilization in the cavity is a key factor contributing to the ethylene-air CRD wave propagation. For L_C = 0 or 20 mm, ethylene-air CRD waves propagate as two-waves in homo-rotating mode with larger operating range and higher outlet pressure. When ER is 1.02 and L_C = 20 mm, the propagation velocity of CRD wave is 1234.81 m/s accounting for 67.5% of corresponding CJ velocity. For L_C = 40 or 60 mm, CRD waves propagate as two-waves in hetero-rotating mode with smaller operating range and lower outlet pressure. Through analysis from the high-speed photography images, the flame luminance in re-circulation zone gradually decreases with the cavity moving downstream. The CRD wave flame and re-circulation zone flame distribution verify the supposition that the flame stabilized in the cavity in the detonation wave front area works as the pilot flame providing maximal effect. Once the cavity is downstream arranged out the detonation wave front area, the effect of cavity stability will be weak and CRD waves will propagate in hetero-rotating mode to release heat. But the effect of afterburing may be feasible. The study will improve the combustor design of CRD Engine fueled by hydrocarbon fuels and enhance the understanding of flame dynamics of CRD waves.

Acknowledgements

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