Number Change Of Detonation Waves In Hollow Continuous Detonation Chamber

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1. Introduction

A three-dimensional numerical simulation of continuous detonation chamber (CDC) with hollow combustor is performed to analyze wave structure evolution systematically. Hydrogen-air reaction and one-step chemistry model is used. The governing equation is the Euler equation, with 5th order MPWENO scheme and 3rd order TVD Runge–Kutta scheme. Wave structure evolution is classified into five categories, namely symmetric detonation collision, asymmetric detonation collision, detonation/shock collision, abscission of detonation tail, and shock wave to detonation transition. All these phenomena affect the number of detonation waves in the combustion chamber. The research mentioned above is based on hollow combustor model, which was first proposed by Shao et al. [1] and Tang et al. [2]. The feasibility of rotating detonations in hollow combustors has already been proved, e.g., with methane–oxygen mixtures by Lin et al. [3].

2. Collision of symmetric detonation waves

Figure 1 shows two detonation waves with approximately the same intensity colliding around 194 μs. The local pressure and temperature reach the highest value at the moment of collision and then decrease rapidly. During the entire collision period, the pressure is rarely lower than 30 atm (stagnation pressure p_0), which prohibits the fresh gas from getting into the chamber, causing the subsequent detonation waves extinguished. The collision transforms the detonation waves into shock waves propagating in opposite directions. The inner parts collide with each other first and the collision point moves from the inner part to the side wall.

3. Collision of asymmetrical detonation waves

Figure 2 shows the collision of asymmetrical detonation waves happening around 292 μs. The clockwise detonation wave marked with 1 exists outside of the dashed circle, while the counterclockwise detonation

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wave marked with 2 extends to the inside. During collision, the detonation waves cancel each other outside of the dashed circle just like the collision of symmetric detonation waves. However, the inner part maintains a counterclockwise detonation wave marked with 3, which causes the change of number difference. This is because the fresh gas inside the dashed circle is adequate for the maintaining of detonation 3.

4. Detonation/shock collision

Figure 3 shows a clockwise detonation wave and a counterclockwise shock wave colliding around 124 μs. Bluemner et al. [4] found in experiments that there were counter-rotating waves composed of a primary wave and a much weaker wave. They call this mode Single Wave with Counter-Rotating Component (SWCC). This mode is in accord with detonation/shock collision.

After collision, the pressure and temperature of the detonation wave change slightly while the height of detonation front decreases dramatically. There are two major causes for the decrease. First, the height of detonation is equal to the height of fresh gas layer at the detonation front, as shown in Figure 4(c). Figure 4(b) shows that the axial component of velocity is zero at position 1, which indicates no fresh gas is injected into the chamber at the shock front. Additionally, arrow 2 in Figure 4(d) shows that the mass of fresh gas decreases when the shock wave passes, which indicates part of the fresh gas is burnt by deflagration. Second, arrow 3 in Figure 4(b) shows that the shock wave compresses the fresh gas. The decreasing of the amount of fresh gas and the compression by shock waves lead to the decrease in the height of detonation front.

5. Abscission of detonation tail

Figure 5 shows the abscission of detonation tail around 300 μs. This phenomenon is quite common in hollow combustor. At 296 μs, the detonation waves are in arc shape, extending to $R = R_{\text{inner}}$. No fresh gas is injected inside the region of $R < R_{\text{inner}}$, leading to the combustion extinguished in this region. The detonation waves are divided into two parts, forming tails 1 and 2. Tail 1 gradually becomes a counterclockwise detonation wave, while tail 2 hits the side wall and becomes two detonation waves propagating in opposite directions. The different evolution processes can be explained by the velocity. Gas at the position of tail 1 has big counterclockwise velocity, causing tail 1 to become a counterclockwise detonation wave. However, gas at the position of tail 2 has almost no circumferential component of velocity. Instead, it has a large radial component of velocity, which makes abscised tail 2 hit the side wall vertically and become two detonation waves.

6. Shock wave to detonation transition

Figure 6 shows how a shock wave becomes a detonation wave. The shock wave 1 created by a detonation/detonation collision propagates in the clockwise direction and burns fresh gas near the headwall, shown by arrow 2. At 154 μs, the flame surface reaches the headwall, creating a region of high pressure and temperature. Indicated by arrow 3 in the circumferential velocity contours, this region has a high clockwise velocity, which is the reason for the production of the clockwise detonation wave.

At the same moment, the shock wave shown in Figure 7 also turns into detonation waves. At position 2, there is a surface of pressure discontinuity due to the injection of fresh gas, leading to a region of minus axial velocity. The shock wave 1 moves toward the headwall and reaches the surface of pressure discontinuity at 150 μs, causing the fresh gas to be burnt by deflagration at position 3. The flame surface reaches the headwall vertically at 158 μs, forming two detonation waves propagating in opposite directions.

7. Number changes of detonation waves

According to previous discussion, all the cases of new detonation wave(s) formation are listed in Table 1. Collision of symmetric detonation waves decreases the number of detonation waves of both directions. However, it cannot change the number difference. Detonation/shock collision do not change the number of detonation waves. The rest three scenarios can create new detonation waves, which affects the net number of detonation waves in the combustion chamber. In RDEs we are interested in the wave number when stable. Therefore, we should focus on the column of Single Detonation Waves. Collision of asymmetric detonation wave, abscission of detonation tail, and shock to detonation transition can create single detonation wave, which is essential to the change of net wave number.

Table 1 Cases of new detonation wave(s) formation under different conditions. Symbol × means there are new detonation waves, symbol ○ means no new detonation wave forms.

	Single Detonation Wave	Opposite-direction Detonation Waves
Collision of symmetric detonation waves.	×	×
Collision of asymmetric detonation waves.	○	×
Detonation/shock collision.	×	×
Abscission of detonation tail.	○	○
Shock to detonation transition.	○	○

Inspired by this idea, we draw Figure 8 that shows the number of clockwise and counterclockwise waves as well as the number difference of them. In Figure 8(c), there exist an increase at 154 μs and 3 decreases at 292 μs, 306 μs and 316 μs, respectively. The increase at 154 μs is caused by shock to detonation transition. The decreases at 292 μs and 316 μs are caused by the collision of asymmetric detonation waves. The decrease at 306 μs is caused by the abscission of detonation tail. In the end, the stable condition is one counterclockwise detonation wave.

8. Conclusions

Two symmetric detonation waves turns into two opposite-direction shock waves after collision. Collision of two asymmetric detonation waves can only create one detonation wave. Collision of shock wave with detonation wave decreases the detonation height instead of extinguishing the detonation wave. Abscission of detonation tail can create single detonation wave or two opposite-direction detonation waves. A shock wave can transit to one detonation wave or two opposite-direction detonation waves. Collision of asymmetric detonation wave, abscission of detonation tail, and shock to detonation transition are essential to the change of net wave number.

Acknowledgements

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Figures

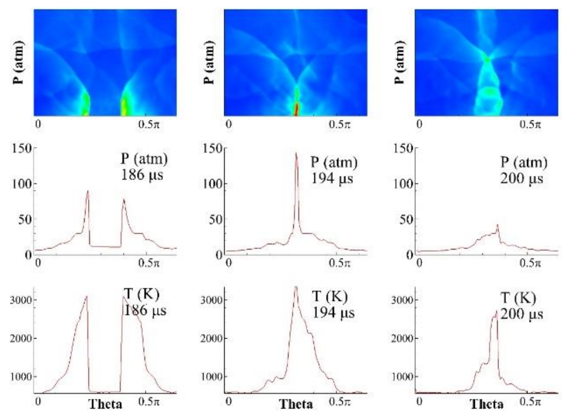

Figure 1 Detonation/detonation collision on the $r = R_{\mathrm{outer}}$ slice. (a) Unwrapped maps of pressure contours. (b) Pressure distribution on the headwall. (c) Temperature distribution on the headwall.

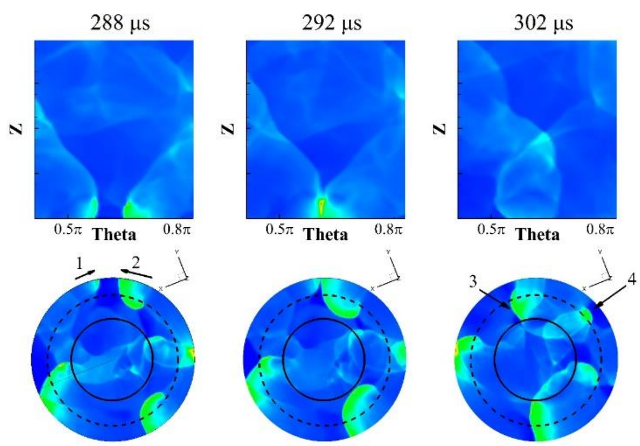

Figure 2 Unwrapped maps and bottom views of pressure contours at $\mathrm{t} = 288$ μs, 292 μs and 302 μs. 1-Clockwise wave; 2-counterclockwise wave; 3-remaining detonation wave; 4-abscising part.

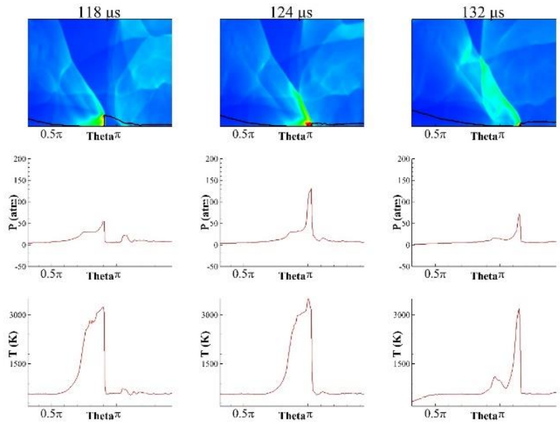

Figure 3 Detonation/shock collision process on the $r = R_{outer}$ slice. (a) Unwrapped maps of pressure contours of this slice. (b) Pressure on the headwall. (c) Temperature on the headwall.

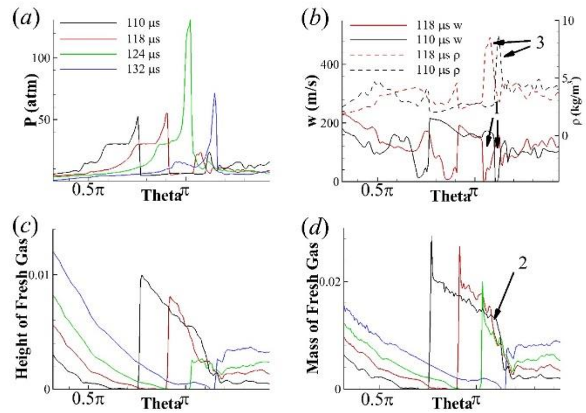

Figure 4 Quantities on the $r = R_{outer}$ slice and on the headwall. (a) Pressure; (b) axial component of velocity and density; (c) height of fresh gas layer; (d) mass of fresh gas.

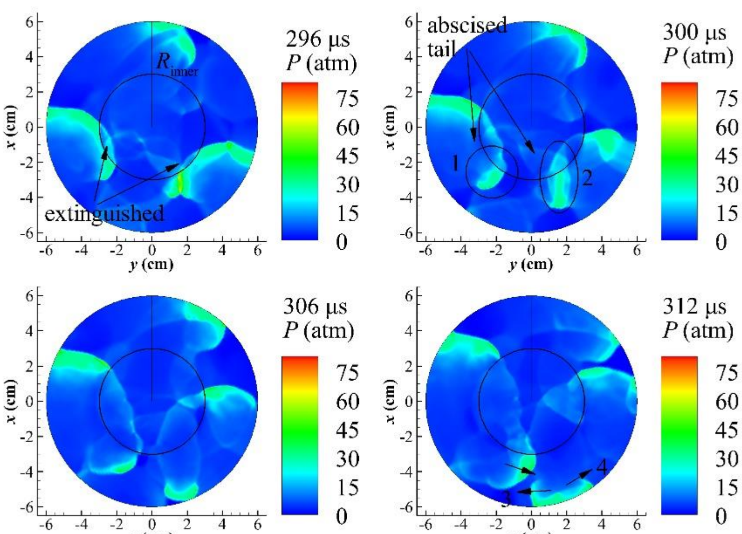

Figure 5 Bottom views of pressure contours at t = 296 μs, 300 μs, 306 μs and 312 μs, respectively.

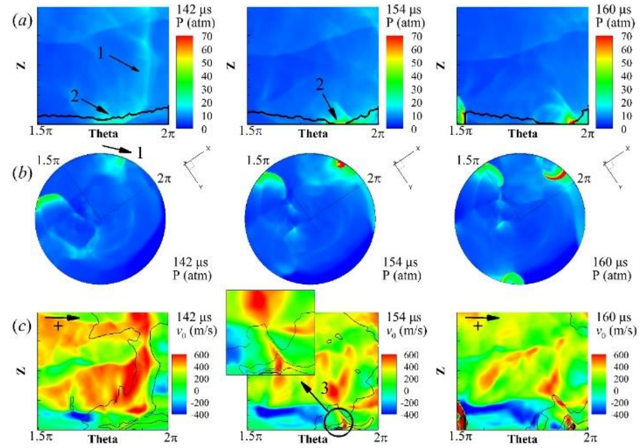

Figure 6 Contours at $t = 142$ μs, 154 μs and 160 μs, respectively. (a) Unwrapped maps of pressure contours with lines separating fresh gas and combustion products; (b) Bottom views of pressure contours; (c) Unwrapped maps of circumferential velocity contours with lines of pressure.

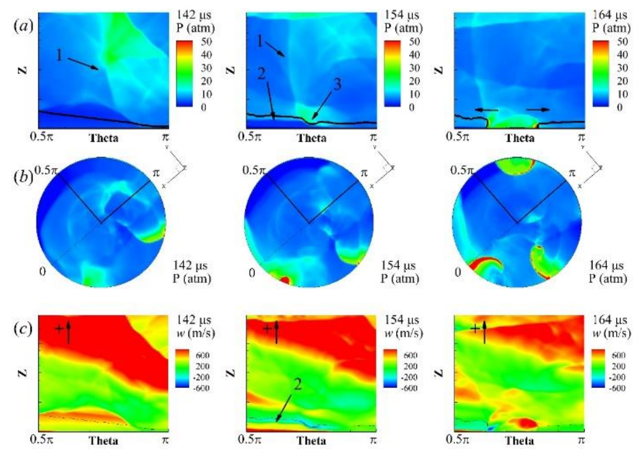

Figure 7 Contours at $t = 142$ μs, 154 μs and 164 μs, respectively. (a) Unwrapped maps of pressure contours; (b) Bottom views of pressure contours; (c) Unwrapped maps of axial velocity contours. Lines in (a) and (c) separates fresh gas and combustion products. 1-Shock wave; 2-surface of pressure discontinuity; 3-intersection of 1 and 2.

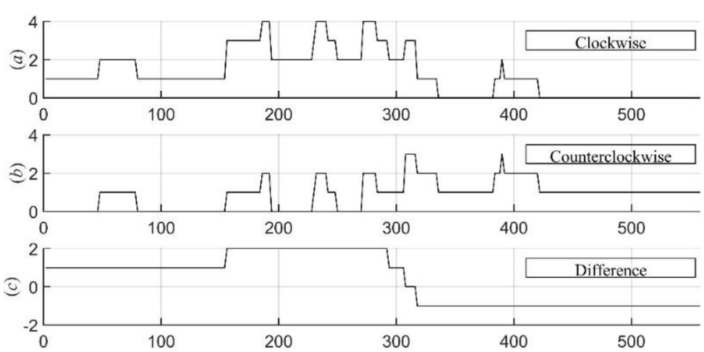

Figure 8 Number of detonation waves. (a) Clockwise waves (b) counterclockwise waves and (c) clockwise waves minus counterclockwise waves.