Numerical Investigation of the Instability of Continuous Detonation Engine

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1 Introduction

It is an essential requirement to run stably for a propulsion system. However, under practical conditions, detonation waves are not always stable in continuous detonation engine (CDE). So it is critically significant to investigate the stability of the CDE. Some researchers paid their attention to the effect of the mass flux on stability of the CDE. Bykovskii et al. [1] found that higher mass flux generally would cause more detonation waves by experiments. Liu et al. [2] showed that the strength of detonation waves oscillated periodically when the mass flux increased. Afterwards, Wu et al. [3] numerically explained this phenomenon by increasing the injection total pressure to promote the mass flux. The others deeply analyzed the mechanism of instability in the CDE. Wang et al. [4] and Vijay Anand et al. [5] both identified three or four kinds of fundamental instabilities in the CDE by experiments, and they both considered the low frequency instability was caused by the interaction of the injection of fresh gas and detonation waves. Nevertheless, Due to the difficulty of three-dimensional visualization by experimental measurement devices, the information in the CDE flow field is so limited as not to clearly explain the mechanism of this instability.

In this article, a numerical simulation is performed to investigate the mechanism of this instability. The injection velocity and pressure on the inlet wall are discussed based on the time evolution of detonation waves. The pressure gradient in overall flow field is evaluated to reveal the interaction between the injection of fresh gas and detonation waves.

2 Physical Modeling and Numerical Method

The chamber of the CDE is a coaxial annular cavity. Assuming that the depth along the radial direction is much smaller than the diameter and axial length, and then, the flow-field can be approximated as a two-dimensional cylindrical chamber without thickness. In this study, the radius and length are 0.01 m and 0.05 m, respectively. One convergent nozzle are placed on each grid on the inlet wall. The stoichiometric H_2/air

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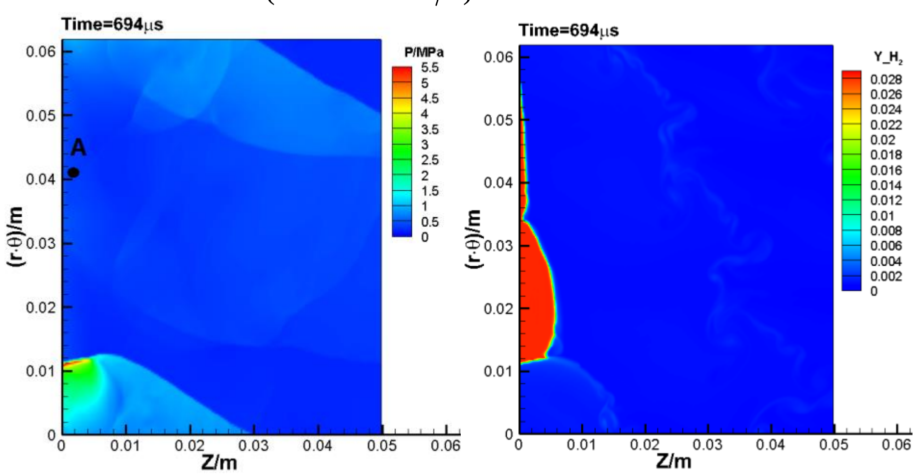
are injected into the chamber through convergent nozzles with the injection total pressure P_{total} of 0.5 MPa. The corresponding critical pressure P_{cr} is 0.264 MPa.

The flow-field is governed by the two-dimensional conservative Euler equations in cylindrical coordinates, with source terms due to the H_2/air detailed chemical reaction model [6]. Strang's operator splitting method is employed to treat the stiffness of the equations. The spatial terms are discretized with a 5-order MPWENO scheme, and the temporal terms are integrated with the 3-step Runge–Kutta method.

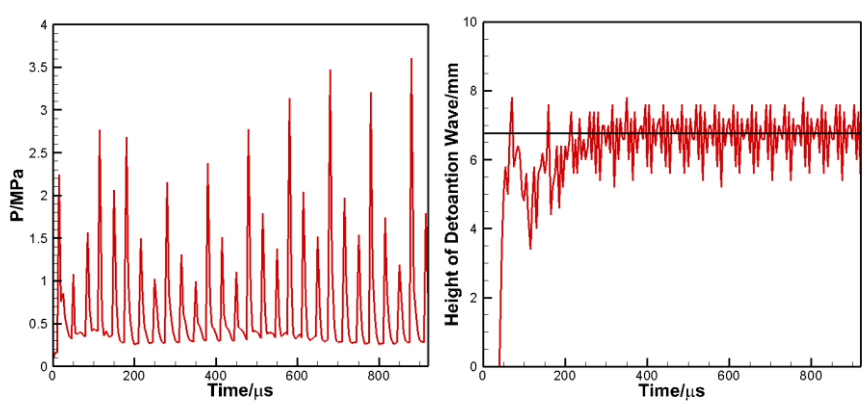
3 Results and Discussion

There forms a detonation wave rotating circumferentially at the head of the chamber, shown in Figure 1. The detonation wave is unstable. Figure. 2 shows the periodic oscillations of the height and strength of the detonation wave. The shape of the fresh fuel layer is obviously irregular. By calculation, the average rotational cycle and velocity of the detonation wave are $32.5\mu s$ and $1932.3\,m/s$, respectively. The velocity is 96.6% of the theoretical CJ value (about $2000\,m/s$) under the same conditions.



(a) (b)

Figure 1. Instantaneous contour of (a) pressure and (b) mass fraction of H_2



(a) (b)

Figure 2. Temporal evolution of (a) pressure of point A and (b) detoantion wave height

The injection velocities at the points located between $A(0,0.0121)$ and $C(0,0.0554)$ are recorded and their integral is calculated from $670\mu s$ to $694\mu s$, forming the border line of the fresh fuel layer, shown in Figure 3. The border line of the fresh fuel layer given by the integral calculation is in good agreement with that given by simulation, especially, the concave at point B. Therefore, the irregular shape of the fresh fuel layer is caused by injection conditions. Nine points are evenly spaced between $(0,0.032)$ and $(0,0.038)$, where pressures and injection velocities are recorded (see Figure 4). The pressure rises successively from point 1 to point 9 when the detonation wave sweeps. Afterwards, the pressuer on each point declines gradually due to the effect of rarefaction waves. The fresh fuel can be injected into the chamber through the point when P_{total} is higher than the pressure at the point.

The fresh gas is successively injected into the chamber through points 1, 2, and 3. The fuel injection is continuous at these three points whose pressures are always lower than P_{total}, though it is found that there is slight pressure oscillation, shown in Figure 4(a). However, the pressure oscillation at points 4, 5, and 6 is so large that sometime the pressure becomes higher than P_{total}, shown in Figure 4(b). So the injection is cut off for a perod of time until the pressure becomes lower than P_{total}. The situations of points 7, 8 and 9 is similar with those of points 1, 2 and 3, shown in Figure 4(c). The only difference is the total time for injection at point 7, 8 and 9 is shorter. The accumulation of fresh gas at each point is calculated from $670\mu s$ to $694\mu s$, in Table 1. Point 5 (overlaping with point B) has the smallest accumulation of fresh gas, which explains why it becomes a concave point in Fig. 3

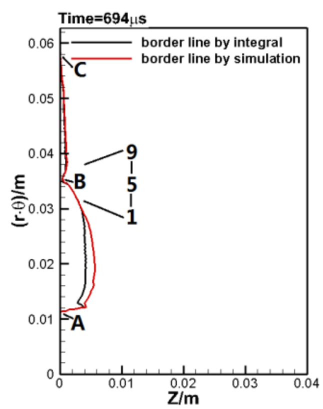
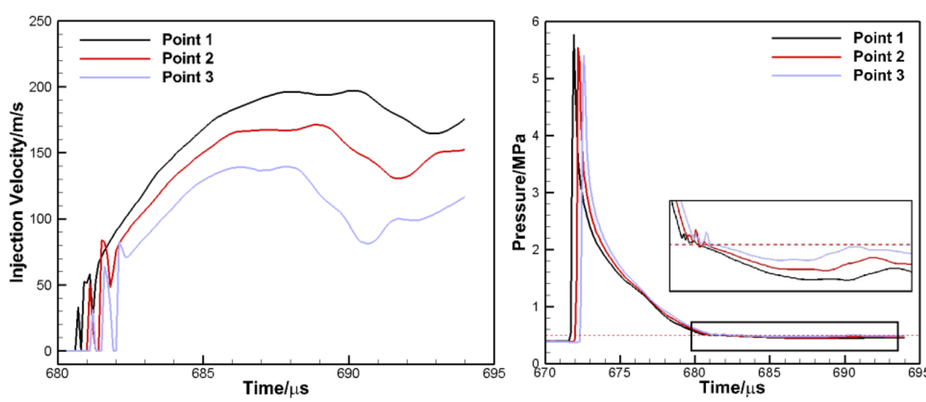
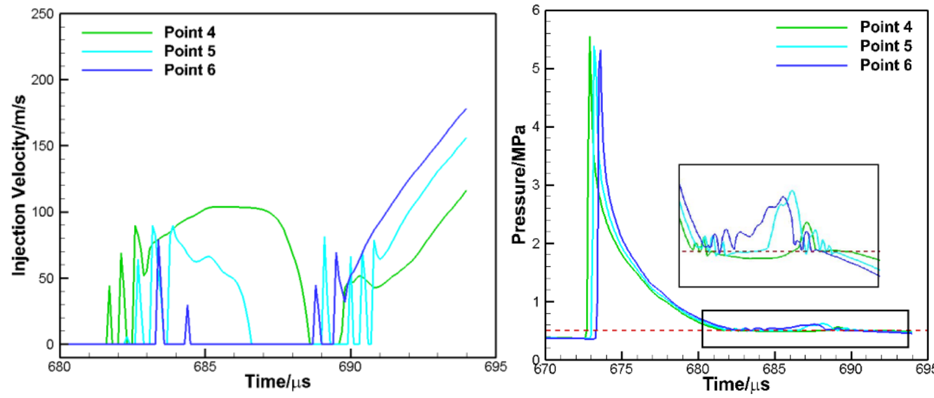


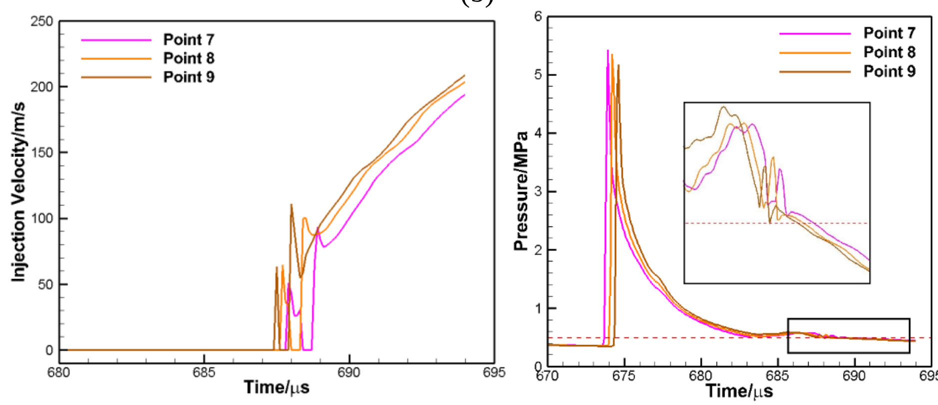
Figure 3. Border line of fresh gas



(a)



(b)



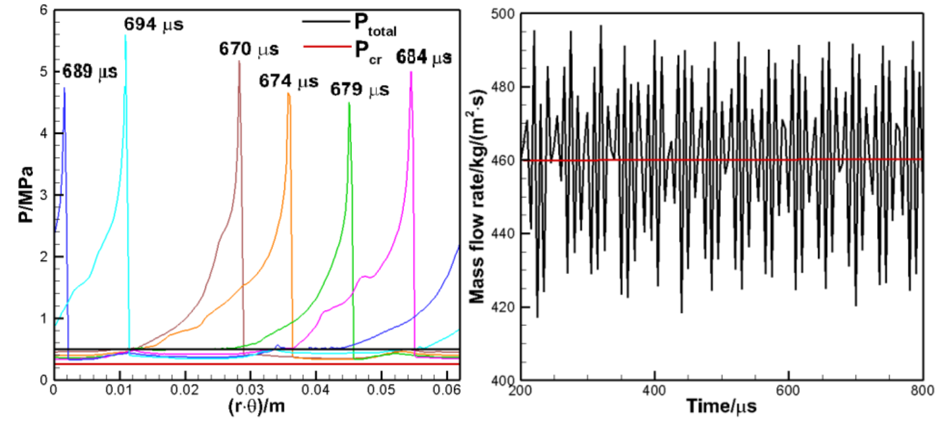
(c)

Figure 4. Temporal evolution of injection velocity and pressure at
(a) point 1-3, (b) point 4-6, (c) point 7-9

Table 1: Accumulation of fresh gas on 9 points

Type	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9
Accumulation of fresh gas/mm	2.2	1.8	1.4	0.8	0.5	0.6	0.7	0.8	0.9

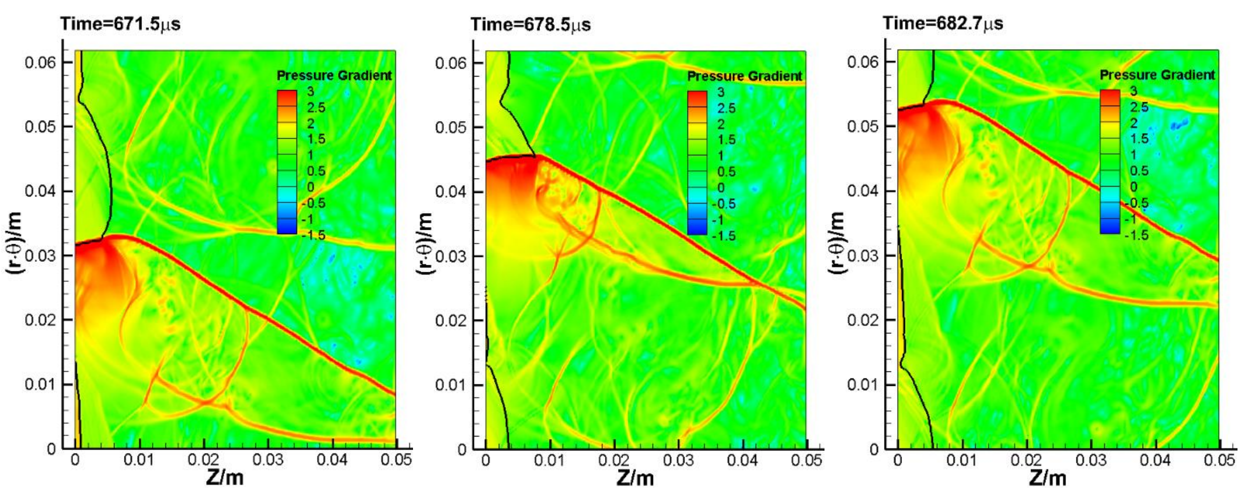
Figure 5(a) shows the pressure distribution of the overall inlet wall is similar every moment. Furthermore, the pressure in each location of the inlet wall is higer than P_{cr}. Therefore, the inlet convergent nozzles are not choked. Any pressure oscillation can affect the injection velocity of convergent nozzles. Because the height and strength of the detonation wave oscillate periodically, the pressure oscillation in the flow field must be periodic. As a consequence, the mass flow rate is periodically fluctuating, shown in Figure 5(b). The fluctuating mass flow rate can aggravate oscillations in the flow field.



(a) (b)

Figure 5. (a) Pressure distribution of overall inlet wall (b) Temporal evolution of mass flow rate

We also compute the pressure gradient in order to find reasons why there exist some pressure oscillations in the flow field. The logarithmic pressure gradient contour are shown in Figure 6. From $671.5\mu s$ to $678.5\mu s$, the height of the detonation wave changes from the lowest to the highest and then reaches the lowest again at $682.7\mu s$. The periodic oscillation of the detonation wave induces a group of weak shock waves, making the flow field extremely complicated. These weak shock waves propagate to the inlet wall, collide with it, reflect, and then spread downstream. At $686.6\mu s$, some weak shock waves collide with the fresh fuel layer at point B (point 5) and cause a pressure rise. In this case, the fuel injection is cut off until $t = 690.8\mu s$. Fresh gas starts to be injected through point 7, 8 and 9 when point 5 is blocked. The process coincides with the evolution of the velocity at point 5 in Figure 4(b). Some weak shock waves can also collide with the fresh fuel layer at points 1-4 and points 6-9. But the pressure oscillations caused by weak shock waves are so slight as not to block fuel injection at these points, which explains the phenomena in Figure 4(a) and 4(c).



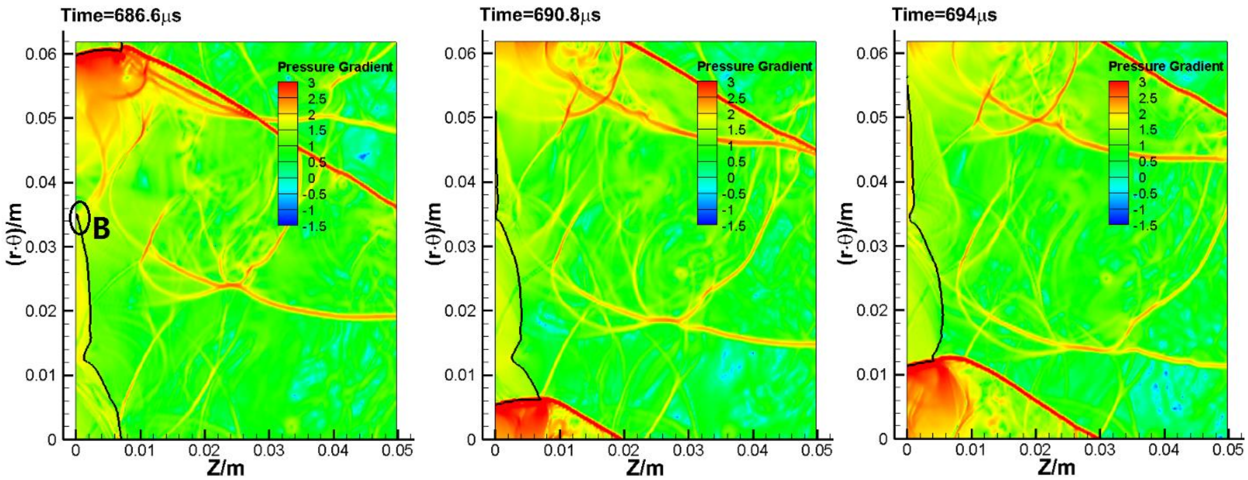


Figure 6. Logarithmic pressure gradient contour of 6 key moments

4 Conclusion

An instability phenomenon of the detonation wave is discussed in details. The detonation wave oscillates due to the fuel injection conditions. The oscillation of detonation wave produces a group of weak shock waves, making the flow field very complicated. Some weak shock waves collide with the inlet wall and cause an instant pressure rise, blocking the fuel injection in some locations. As a consequece, the fresh fuel layer presents an irregular shape, which in turn causes the detonation wave oscillating. Furthermore, convergent nozzles are not choked, making the mass flow rate fluctuating due to pressure oscillations. The fluctuating mass flow rate can aggravate oscillations in the flow field, making the fresh fuel layer irregular as well. This irregularity remains in the flow field, so does the instability of the detonation wave.

References

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