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Three-Dimensional Numerical Simulation of Rotating Detonation Engine with the Hollow Combustion Chamber

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Abstract: Using detonation in engines would be an extremely efficient way to create enormous thrust. In order to bring detonation closer to practical application, a totally new model of combustor for the rotating detonation engine is developed in this letter which is called the hollow combustion chamber. Three-dimensional numerical simulation is done to verify the possibility of detonation propagation in combustor of this type utilizing the one-step chemistry kinetic model and the Eular function in cylinder coordinates ignoring diffusion, viscosity and thermal conductivity. Also, an overlapping grid formed by a rectangular grid and a body-fitted grid is used to avoid the singularity problem at the central axis. The simulation shows the unstable process of repeated ignition and extinction at initiation stage. The detonation initiated by one detonation wave finally converges to a propagation structure of two central symmetric detonation waves without any artificial disturbance and they rotate inside as a steady state.

Keywords: hollow combustion chamber, rotating detonation, continuous, 3D simulation, self-maintenance stability

1 Introduction

Combustion processes can be divided into two categories: the deflagration mode and the detonation mode. The combustion in conventional engines, such as gas turbine engines and ramjet engines, belongs to the deflagration mode. The propagation velocity of deflagration wave is about several meters per second, and it is about several thousand meters per second for detonation wave propagating in gas mixture. Thus detonation allows more intense and rapid combustion, which means that enormous thrust can be created in a smaller combustor. Furthermore, since detonation is a nearly isochoric combustion process, it is more thermodynamically efficient than the conventional isobaric combustion. Therefore, using detonation in the engine would be extremely efficient and there have been numerous research efforts at taking advantages of the potential of detonation for propulsion applications.

There are three ways to use detonation wave (DW) propagation in order to create thrust: the pulse detonation engines (PDEs), the standing oblique detonation engines (SODEs) and the rotating detonation engines (RDEs). In a PDE, fuel is combusted in the mode of detonation by high-frequency ignitions [1]. The frequency and ignition energy are the obstacles to overcome for this type of engine to be applied to practice. As for the SODE, reactants are fed from the front-end at a high velocity. Meanwhile, fuel inside the engine is consumed to power the engines by DWs or oblique DWs at DW propagation velocity relative to gas mixture [2]. The two velocities must match to make sure that DWs or oblique DWs can stay at their stable positions. The DWs may move to the head or tail end if the injection velocity increases or decreases, and quench. So the SODEs require stability. A rotating detonation engine (RDE) provides an alternative way to apply detonation power. Fuel for a RDE is continuously fed through holes or slits along the axial direction on the head wall. Rotating DW propagates azimuthally in the head of the combustor. RDEs can continuously work without the aforementioned problems such as multi-time ignition, low operation frequency and sensitive dependence of stability.

The basic concept behind a RDE, also known as continuous detonation engine (CDE), was firstly introduced by Voitsekhovskii in the 1960s [3]. In recent years, vast amounts of work have been done in the study of RDEs, which make RDEs closer and closer to the practical application. In the experimental study, a serial of experiments by Bykovskii et al [4] achieved both liquid and gas fuel detonation in combustors with injection flow at different speeds and with different combustor shapes. Kindracki and Wolanski have experimentally produced the continuously propagating DW for a long time of about 150ms, and the DW has continuously propagated thousands of laps inside. Also, significant propulsive performance was detected [5].

Besides experimental researches, numerical simulations are always needed to reveal the inner flow field in RDEs and propagation mechanism because of the fast propagation velocity of the DW and difficulty in three-dimensional visualization. About numerical simulations of RDEs, the former works [6, 7, 8] all investigated co-axial annular combustor. Although the extensive studies of co-axial annular combustor structure show that it's steady for DW propagation, this model of RDE combustor still need to be improved because of difficulties in cooling a real engine since the temperature inside a RDE combustor can reach as high as 3000K. In this letter, a totally new model of RDE combustor is presented, which is called the hollow combustion chamber. Contrast to a co-axial annular combustor, a hollow combustion chamber has no inner wall. It only has an annular outer wall to keep DWs inside the chamber. By this way, the difficulties in engine cooling will be greatly reduced. In order to prove that in the hollow combustion chambers DWs can propagate stably just as in the co-axial annular combustors, a three-dimensional numerical simulation is done, which investigates the physical phenomenon of continuously rotating detonation propagation in the hollow combustion chambers.

2 Problem Statement

As shown in Fig.1, fresh gas is continuously fed into the combustor through small slits or holes located at the outer annulus (3cm r<6cm) of the head wall. The inner area (r<3cm) at the head wall is solid wall without injection nozzles. Detonation products are ejected out through the exit end to provide thrust. The outer annulus is initially filled with quiescent, combustible gas mixture at pressure p = 0.103MPa and temperature T = 300K while the inner area is initially filled with combustion products. The DW is ignited by a branching pre-detonation tube that is connected tangentially to the outer wall of the combustor. In numerical simulation, a section of the classical ZND detonation wave is set to substitute the pre-detonation ignition. After ignition, the DW continuously propagates azimuthally around the combustor.

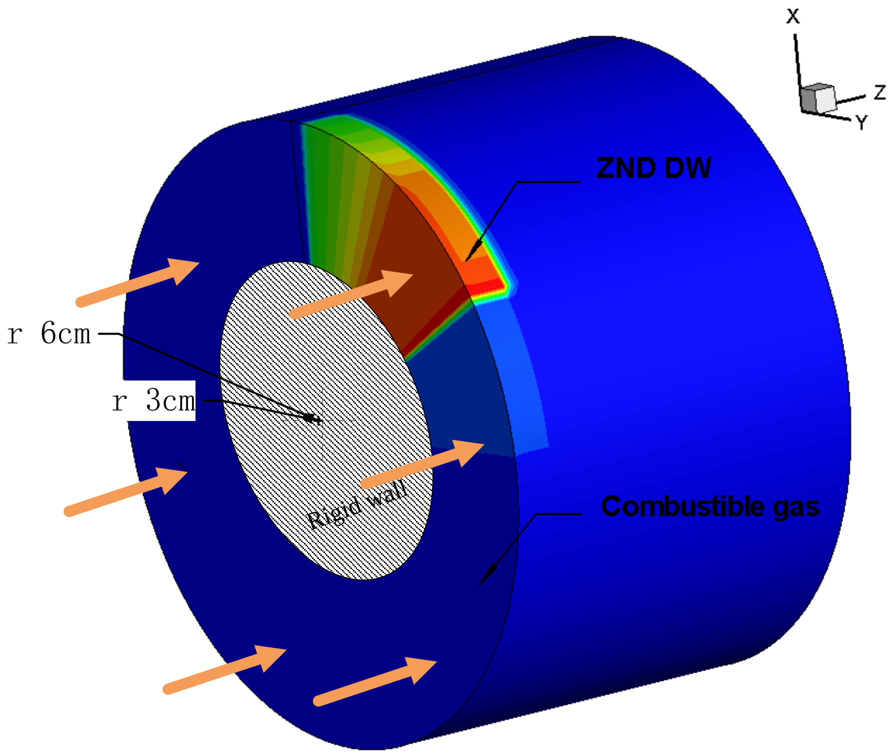

Fig.1 Initial conditions in the hollow combustion chamber

A premixed and stoichiometric H_2/O_2 mixture injection condition is set according to the local wall pressure following the Laval tube theory [8]. The injection stagnation pressure is p_0 = 2MPa and the environment pressure p_∞ is 0.1MPa. The boundary condition at the injection position is specified from the isentropic relation according to pw, which is the local environment pressure near the wall. Also, a one-step chemical kinetic model is used in this simulation. The governing equations are the three-dimensional Euler equations expressed as below in generalized coordinates:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial \xi}+\frac{\partial \boldsymbol{F}}{\partial \eta}+\frac{\partial \boldsymbol{G}}{\partial \zeta}=\boldsymbol{S}$$

where the conservative vector U, the convective flux vectors E, F, G ,and source vector S are, respectively, given as

$$\boldsymbol{U}=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ e\\ \rho\beta\end{pmatrix},\ \boldsymbol{E}=\begin{pmatrix}\rho\bar{U}\\ \rho\bar{U}u+p\xi_x\\ \rho\bar{U}v+p\xi_y\\ \rho\bar{U}w+p\xi_z\\ \bar{U}(p+e)\\ \rho\bar{U}\beta\end{pmatrix},\ \boldsymbol{F}=\begin{pmatrix}\rho\bar{V}\\ \rho\bar{V}u+p\eta_x\\ \rho\bar{V}v+p\eta_y\\ \rho\bar{V}w+p\eta_z\\ \bar{V}(p+e)\\ \rho\bar{V}\beta\end{pmatrix},\ \boldsymbol{G}=\begin{pmatrix}\rho\bar{W}\\ \rho\bar{W}u+p\zeta_x\\ \rho\bar{W}v+p\zeta_y\\ \rho\bar{W}w+p\zeta_z\\ \bar{W}(p+e)\\ \rho\bar{W}\beta\end{pmatrix},\ \boldsymbol{S}=\begin{bmatrix}0\\0\\0\\0\\0\\ \dot{\omega}_\beta\end{bmatrix}.$$

where

$$\bar{\boldsymbol{U}}=u\xi_x+v\xi_y+w\xi_z,$$

$$\bar{\boldsymbol{V}} = u\eta_x + v\eta_y + w\eta_z,$$

$$\bar{\boldsymbol{W}} = u\zeta_x + v\zeta_y + w\zeta_z,$$

The pressure p and total energy e are calculated using equations of state:

$$p = \rho RT$$

$$e = \frac{p}{\gamma\text{-}1} + \rho\beta q + \frac{1}{2}\rho u^2 + \frac{1}{2}\rho v^2 + \frac{1}{2}\rho w^2$$

The mass production rate is:

$$\dot{\omega}_\beta = \frac{d\beta}{dt} = -A\rho\beta \exp(-E_a / RT)$$

where β is the mass fraction of reaction mixture gas. β=1 signifies fresh gas mixture, while β=0 signifies detonation products. Flux terms are solved by the monotonicity-preserving weighted essentially non-oscillatory (MPWENO) scheme. Time integration is performed by the third-order TVD Runge-Kutta method.

Because of the singularity, it is difficult to get a good three-dimensional simulation in a hollow tube. In this letter, an overlapping grid is used, as shown in Fig.2.The inner area is occupied by rectangular Cartesian grids and the outer area is occupied by curvilinear body-fitted grids. Variable information of one grid node is linearly interpolated by the neighbor four grid nodes which belong to the opponent grid system in the overlapping area. The average grid size is 0.4mm along every direction. This reliability of this numerical method and grid dependence has been tested in the previous work. The interpolation relationship is illustrated in Fig. 3. The value at grid point C″ in the rectangular grid is interpolated by the values at its neighboring four grid points in the curvilinear body-fitted grids. The dependent variables at C″ is U(C″). The distance between C″ and its four neighboring points are |C″A|,|C″B|, |C″C|, |C″D|, indicated by S1, S2, S3, S4 respectively. Then the physical variables U(C″) can be interpolated by the following equations:

$$IS_i = \left(\frac{1}{S_i + \varepsilon}\right) / \sum_1^4 \frac{1}{S_i + \varepsilon}$$

Thus

$$\boldsymbol{U}(\text{C}'') = IS_1 * \boldsymbol{U}(A) + IS_2 * \boldsymbol{U}(B) + IS_3 * \boldsymbol{U}(C) + IS_4 * \boldsymbol{U}(D)$$

where ε=1.E-8.

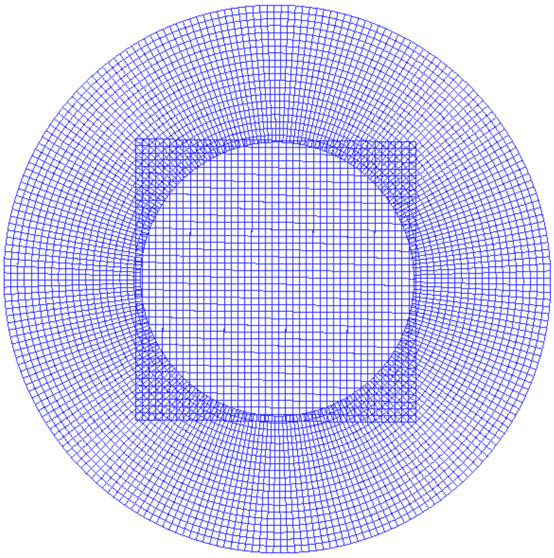

Fig.2 Schematic of the overlapping grid

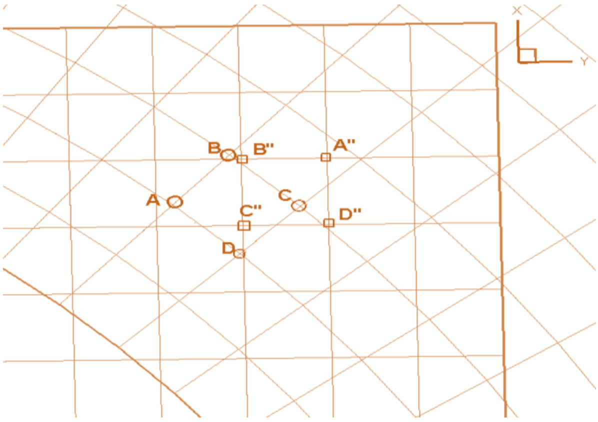

Fig.3 Interpolation on the overlapping grid points

3 Result and discussion

Fig.4 and Fig.5 show the pressure and temperature distribution inside the chamber at 845μs, 850μs, 855μs, and 860μs. It can be seen that two symmetrical rotating detonation waves are formed in

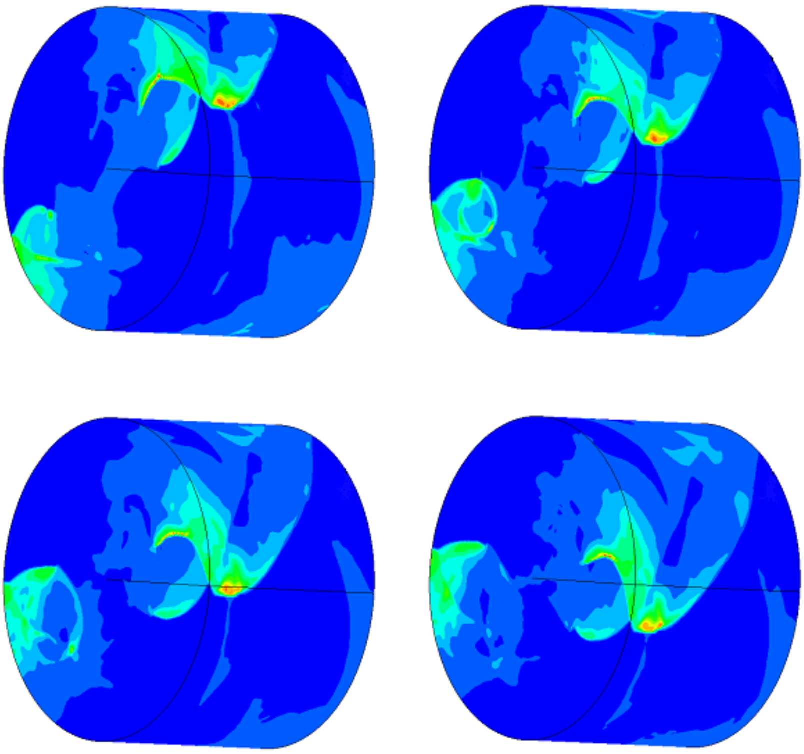

Fig.4 Pressure at 845μs, 850μs, 855μs, 860μs

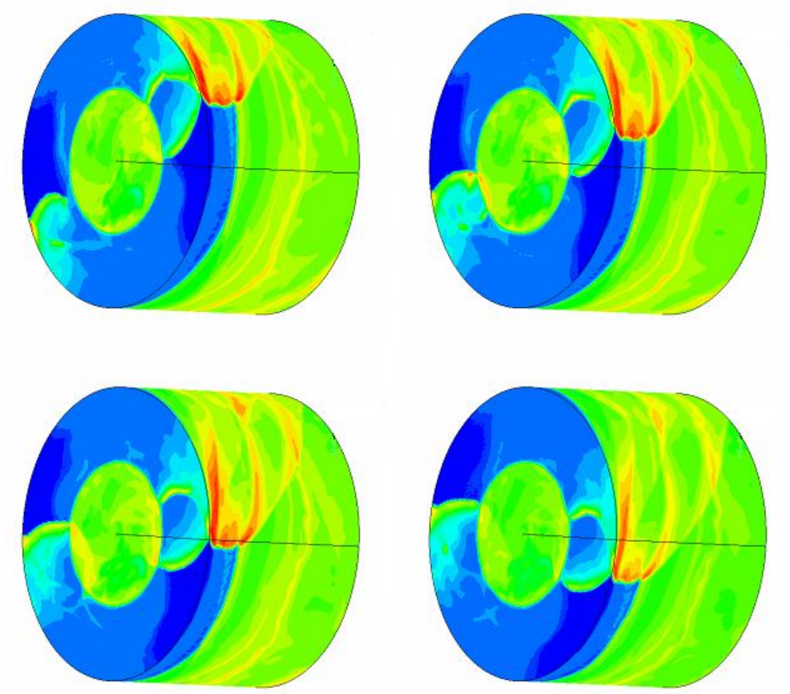

Fig.5 Temperature at 845μs, 850μs, 855μs, 860μs

the combustor and they are in a stable state. Detonation waves mainly propagate in the outer circular region where combustible gas is continuously fed. The pressure changes smoothly at overlapping area of the grids and the central axis, and no numerical oscillation appears, which means the overlapping grids work well.

For more details, the pressure contour at 1360μs is presented in Fig.6. First of all, compared to Fig.5, it shows that waves have the same behavior at 860μs and 1360μs, which means that at this time detonation waves have come to a steady state. Second, in co-axial annular combustors shock waves behind DWs meet the inner wall and reflect, while in the hollow combustor, since no inner wall exists, they extend deep into the combustor, decaying into sound waves, which are shown as wave-3 in Fig.6.

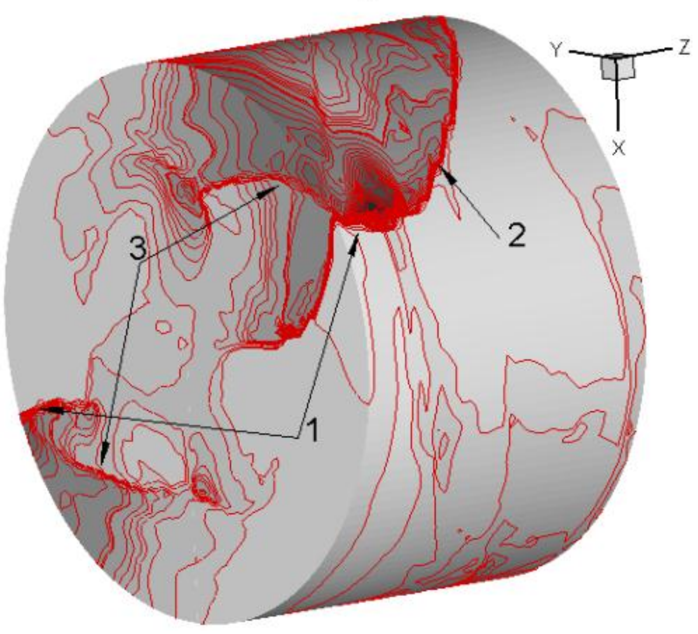

Fig.6 Pressure contour at 1360μs

In order to discuss the evolution from initial state to steady state, pressure and component contours at several moments are presented in one map and then unwrapped circumferentially. Fig.7 shows these coupled maps at 60μs, 100μs, 180μs, 400μs, 700μs and 1360μs. Gray area corresponds to combustible gas while white area corresponds to combustion products. Combustible gas is fed from the bottom margin and combustion products are ejected from the top. It can be seen that in this combustor it takes about 700μs for the DWs inside to evolve to steady state. Moreover, in the process to steady state, DWs develop, collide, degenerate, and sometimes redevelop, which are all shown in Fig.7. Initially, the ZND detonation is injected in tangential direction. It generates wave 1 and at the

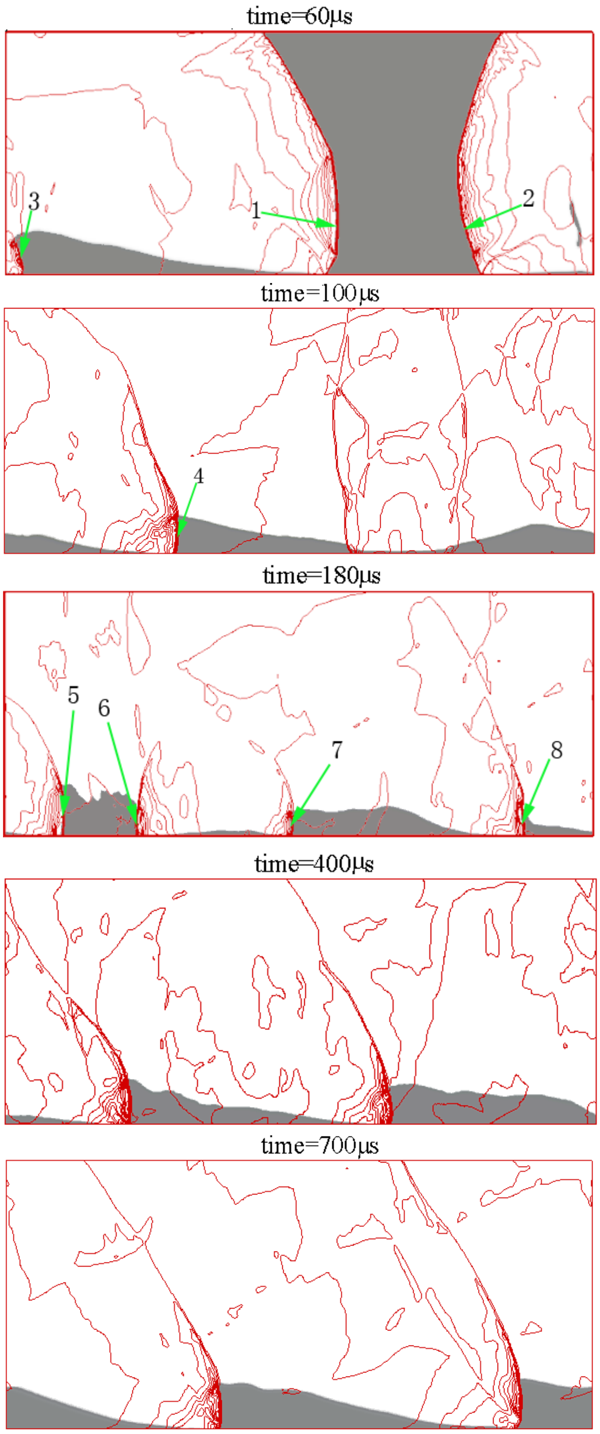

Fig.7 Coupling maps of pressure and component contour at 60μs,100μs, 180μs, 400μs, 700μs and 1360μs

same time the reversed shock strikes the upriver wall and generate two hot spots. These two hot spots develop to wave 2 and 3 once they meet adequate combustible gas, all of which are shown in Fig.7 at 60μs. Detonation waves 1 and 2 propagate and burn the initial combustible gas. Meanwhile, the high pressure at DW area is then reduced to the inlet pressure after passage of the detonation wave which allows the reactants to again feed into the annulus, thereby allowing chemical reactions to continue to sustain the detonation wave. The greater the distance from the DWs is, the lower the pressure will be, and more gas will feed. Fresh combustible gas accumulates to fill a triangle area to get ready to support the next coming DW. If only there is enough fresh gas before the detonation waves, they can keep self-sustaining, such as waves 1, 2, 3, 4, 7. If the gas triangle is not big enough, DW degenerates, such as wave 8. In the early stages, some DWs keep self-sustaining, some degenerate, and others crash and disappear, leaving hot spots, which will evolve to DWs once they meet fresh combustible gas. The waves inside keeps the stabilization process above and at about 400μs becomes close to steady state. At this moment, two gas triangles have been formed and two DWs rotate after these two triangles. At 700μs and 1360μs, the phenomenon remains the same, which means that DWs have been propagating at a stable state. The height of the gas triangles is about 1.5cm.

To verify that the two symmetrical waves are DWs, an observation point is set to record physical signals. It is placed at r=5.8cm, Θ=0， and z=1cm. The pressure at this observation point is shown in Fig.8. In the first 400μs the signal is not very regular since the waves have not yet come to steady state. After that, the signal shows good periodicity, as shown in the time interval marked as B in Fig.8. There are twelve DW signals in period B and the interval lasts 830μs . The period and frequency can be calculated as

$$\mathrm{T} = \frac{t}{n} = \frac{830\times10^{-6}}{12} s = 6.917\times10^{-5} s, f = \frac{1}{T} = 14458\mathrm{Hz}.$$

The speed of the waves can be calculated as

$$v = \frac{L}{T} == \frac{\frac{2\times\pi\times0.058}{2\times6.917\times10^{-5}}\mathrm{m}}{\mathrm{s}} = \frac{2634.3\mathrm{m}}{\mathrm{s}},$$

which is very close to the theoretical detonation velocity in H_2/O_2 mixture. These can verify that the waves inside the combustor are DWs. Two symmetrical DWs propagate inside steadily.

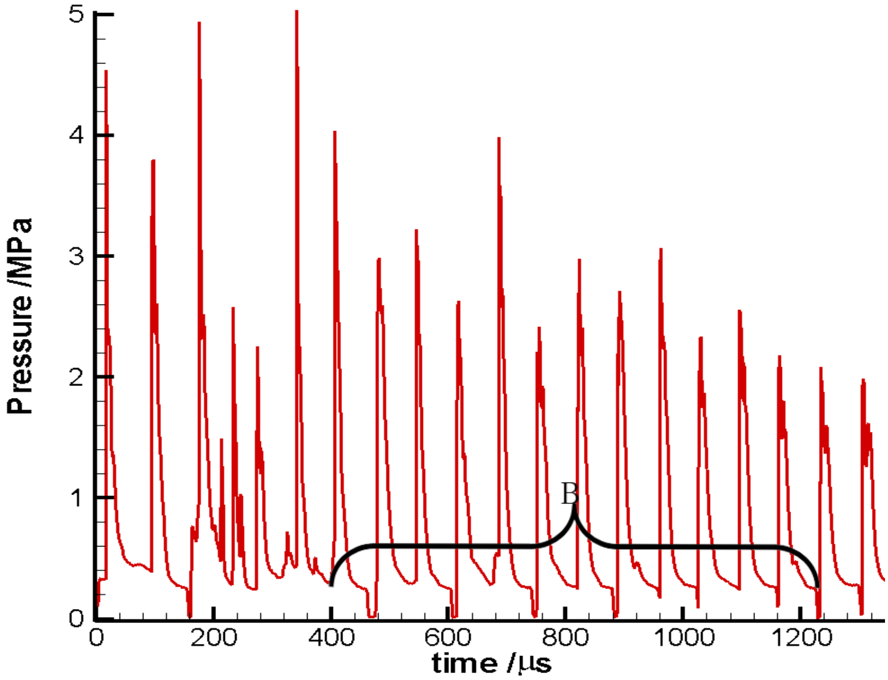

Fig.8 Pressure change at the observation point during 0-1360μs

Fig.9 shows the pressure contour within a cross section at *z*=0.2cm. Two stable detonation waves propagate symmetrically. The width and intensity of the two DWs are similar.

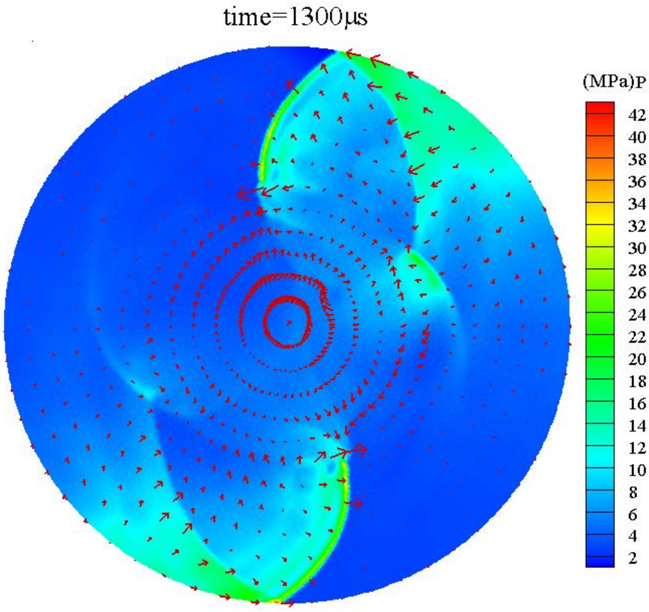

Fig.9 Pressure contour on an axial slice at z=0.2cm at 1300μs

4 Conclusion and Future Work

To conclude, in this paper, a new model of chamber for rotating detonation engine is developed, which is called the hollow combustion chamber. It has no inner wall and only has an annular outer wall to keep DWs inside the chamber. The behavior of DWs inside this combustor, which is a three dimension space, is simulated. The DWs inside the combustor emerge, quench, crash, regenerate, and at about 700μs reach steady state. Two gas triangles with enough height form and after them two symmetrical rotating detonation waves are propagating steadily.

Rotating DWs can continuously propagate in the hollow combustion chamber. The heat load in chambers of this kind can be avoided greatly. It represents an innovative combustor design for the future propulsion. They are easy to substitute the combustors for conventional aviation systems to achieve higher performances. Moreover, the simple RDE design offers simplicity which means dependability and low cost. The hollow combustion chamber brings detonation closer to practical application.

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