Three-Dimensional Numerical Simulation of Rotating Detonation Engines with Hollow Combustor

TANG Xin-Meng[1], WANG Jian-Ping[1], and SHAO Ye-Tao[2]
1 Centre for Combustion and Propulsion, College of Engineering & State Key Laboratory of Turbulence and Complex System, Peking University
Beijing, China

2 Beijing Institute of Astronautical Systems Engineering, Beijing, China

1 Instructions

Combustion can be divided into two categories: deflagration and detonation. The propagation velocity of the deflagration wave is about several meters per second, while it is about several thousand meters per second for a detonation wave propagating in a 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 nearly isochoric, it is more thermodynamically efficient than the conventional isobaric combustion. Therefore, using detonation in engines would be very efficient and many efforts have been made to exploit the potential of detonation for propulsion.

The rotating detonation engine (RDE), also known as the continuous detonation engine (CDE), provides a promising way to make use of detonation. Fuel for an RDE is continuously fed axially through holes or slits on the head wall. Rotating detonation waves propagate circumferentially at the head of the combustor. RDEs can continuously work without the need for multiple ignition, or high operation frequency. Such engines have great potential benefits arising from their simplicity of design and manufacture, lack of moving parts, high thermodynamic efficiency and high energy conversion rate. In recent years, many studies have been done on RDEs, bringing RDEs closer and closer to practical application.

Most recent investigations have worked with a co-axial annular combustor model [1] [2]. Although studies of this combustor structure show that it is steady for detonation wave propagation[3], it still needs further investigation and improvement to become a real engine. A major challenge related to the high power density and compactness of an RDE is the heating [4]. In this work, we present an alternative model of RDE combustors, which we call the hollow combustor. In contrast to the co-axial annular combustor, a hollow combustor has no inner wall. It only has an annular outer wall to keep detonation waves inside the chamber. This greatly reduces the difficulties in engine cooling. To prove that detonation waves can propagate just stably in a hollow combustion chamber as in a co-axial annular combustor, we do a series of three-dimensional numerical simulations to investigate continuously rotating detonation propagation in a hollow combustor.

Correspondence to: simondonxq@gmail.com

2 Physical Model and Numerical Method

As in the annular model, the fresh gas (in this work a hydrogen-air mixture) is continuously fed into the combustor through small slits or holes on the head end. A rotating detonation wave propagates circumferentially near the head end of the combustor and consumes the reactants. The difference is that in this one, the combustor is hollow and no inner wall exists. Premixed reactants are fed only from the outer region of the head end and into the hollow chamber. We set the width of the intake region to be half of the radius R_{outer} of the combustor. On the head end the range $R_{inner}<r<R_{outer}$ is the intake region full of injection nozzles and the other part is the solid wall.

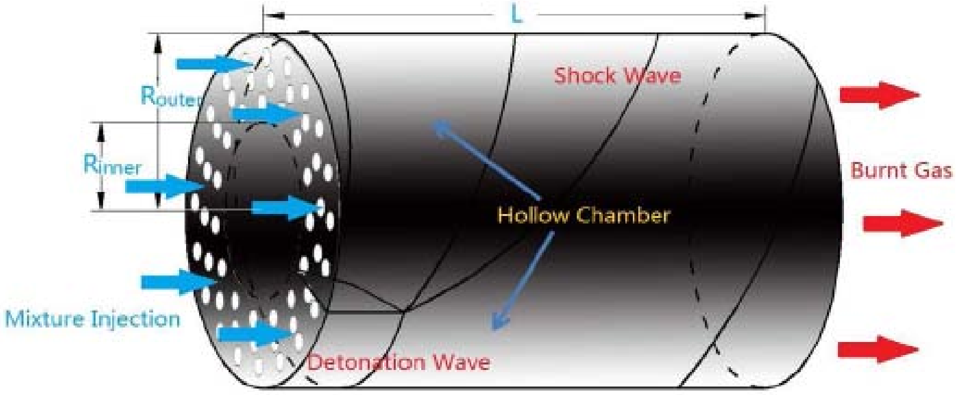

Figure 1. Schematic of a hollow detonation combustor.

To describe a high-temperature, chemical reacting flow, we use the three-dimensional, unsteady Euler equations with source terms using one-step irreversible Arrhenius kinetics for a hydrogen-air mixture. Considering the column shape, the equations can be expressed in generalized coordinates. It has been shown in work on three-dimensional RDE [5] by Yi and co-workers that the one-step kinetics model for a hydrogen-air mixture enables us to determine the most important detonation properties such as the detonation velocity and pressure. The spatial terms are discretized with a five-step weighted essentially non-oscillatory scheme. Time integration is performed by the third-order total-variation-diminishing Runge-Kutta method.

We used an embedded partition grid system, as shown in Figure 2. The inner area is occupied by a rectangular and Cartesian grid and the outer area is occupied by a curvilinear body-fitted grid. Variable information of one grid node is linearly interpolated with the neighboring four grid nodes, which belong to the opponent grid system in the overlapping area. On one hand, this can deal with the singularity problem at the axial position, and on the other hand it can make cells much of a size. The grid independence is presented in [5] from 0.5 mm to 0.025 mm. In this work, the cell size (average cell size in the radial direction) is 0.3 mm.

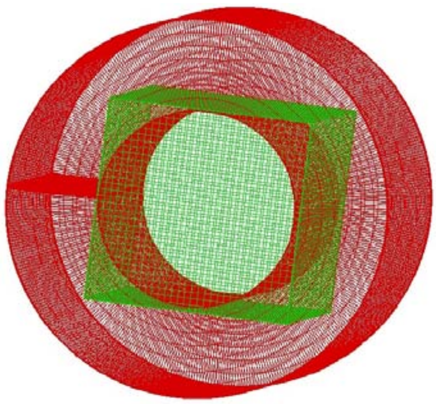

Figure 2. Embedded partition grid system.

The premixed inflow is computed assuming small nozzle inlets on the intake area of the head-end face. Stagnation properties for the premixed gas keep a constant as 3MPa and 600K. The inflow rate varies depending on where the detonation front is. We assume the premixed inflow to be an isentropic expansion and set the mixture injection condition according to the local environment pressure near the wall [5].

In the tube, the outer part $R_{inner}<r<R_{outer}$ is initially filled with a quiescent and combustible gas mixture at pressure p=0.103MPa and temperature T=300K while the inner area is initially filled with combustion products. For the initial conditions of the three-dimensional simulations, we use the results of the 1-D simulations, which are confirmed to be typical Zeldovich-von Neumann-Doering detonation. After ignition and a period of stability, the detonation wave begins to propagate circumferentially around the combustor.

3 Results and discussion

The size of the hollow combustor is changed serially from 6cm to 12cm with an incremental of 2cm to investigate detonation waves' behavior and performance with different chamber sizes. These cases are marked as case 1, case 2, case 3, and case 4. Figure 3 shows the pressure and temperature distribution inside the chamber of case 1 at 1285μs, 1290μs, 1295μs, and 1300μs. One can see that the two detonation waves rotate symmetrically in the combustor during each time period, and both symmetrical waves move forward a certain distance. The detonation waves mainly propagate in the outer region where combustible gas is continuously fed. The pressure changes smoothly at the overlapping area of the two grids and the central axis. No numerical oscillation appears which means the embedded partition grid system works well.

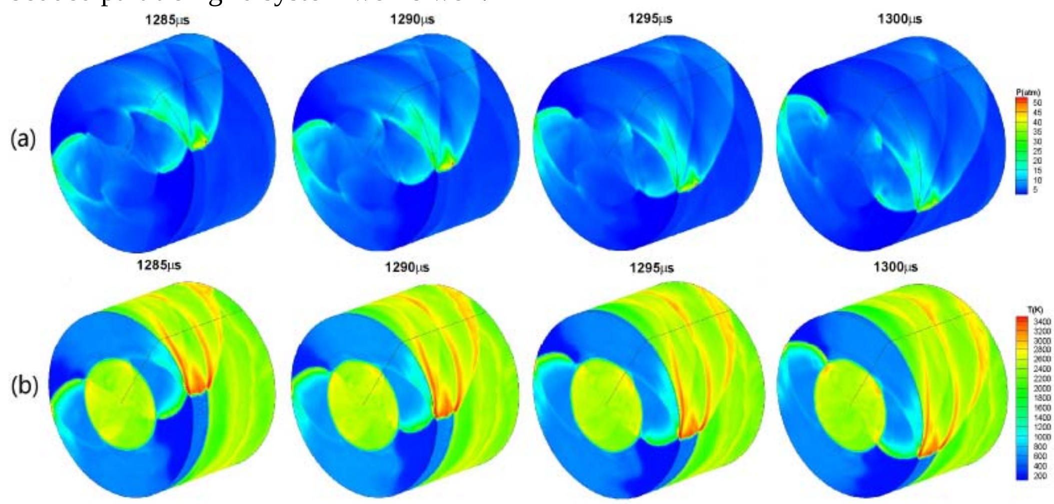

Figure 3. Pressure and temperature contours of case 1 at 1285μs, 1290μs, 1295μs, and 1300μs.
(a) pressure contour, (b) temperature contour.

The calculated propagation velocities of the rotating detonation at r=6cm and r=3cm are 2725.24m/s and 1362.62m/s. The average value of these two velocities or velocity at r=4.5cm is 2043m/s. This speed is very close to the theoretical detonation velocity for an H_2/air mixture. This result suggests that when the rotating detonation wave has a large width in the radial direction, the linear velocity varies with different radial locations r because it has to keep a certain angular velocity ϖ. The velocity is bigger than the C-J value in the outer region and smaller in the inner region. However, the average value of these velocities approaches the theoretical C-J value.

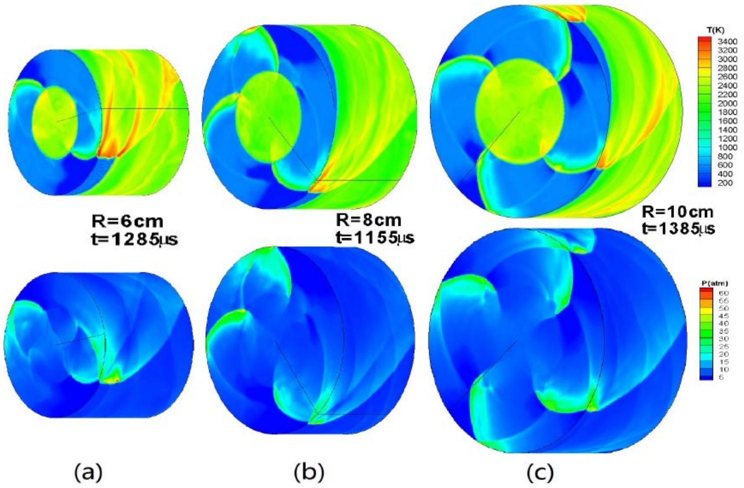

Figure 4. Temperature and pressure contours. (a) case1, R=6cm. (b) case2, R=8cm. (c) case3, R=10cm.

Figure 4 shows the results for case 2 and case 3 together with case 1. The numerical results suggest that in these hollow combustors, detonation waves can still continuously rotate. The hollow RDE model works. There are several detonation waves with a same direction in these chambers. It is found that with a bigger perimeter of the outer wall, the detonation waves inside the hollow chamber tend to have more detonation fronts. The number of detonation wave fronts is 2 in case 1, 3 in case 2 and 4 in case 3. We also find in Figure 4 that when the waves have become dynamically steady, the circumference bounds to be covered by several triangles filled with fresh mixture. In this work we call these triangles gas triangle. The gas triangle is a fresh gas mass behind a detonation wave. It is from the volume of the mixture supplied to the chamber, as shown in Fig. 5. As the detonation wave passes by, the pressure decreases fast because of the expansion wave behind it. Fresh gas is then injected and accumulates. A gas triangle forms and is ready to sustain the coming detonation wave. This process is mainly key why an RDE can rotate continuously.

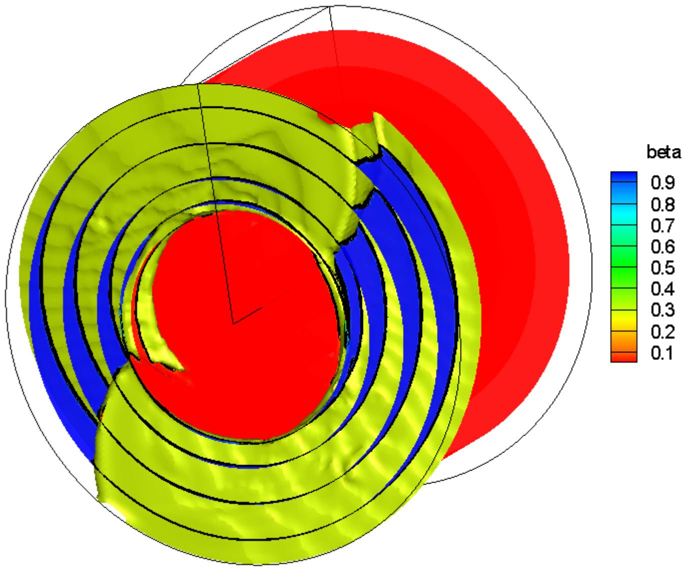

Figure 5. Volume of the mixture supplied to the chamber in case 1. On each r slice it presents a gas triangle.

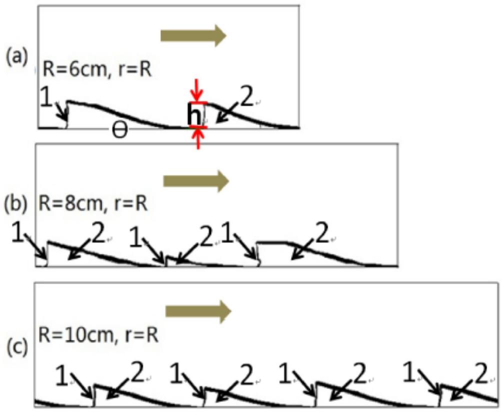

Figure 6. Gas triangles. (a) case 1, *R*=6cm. (b) case 2, *R*=8cm. (c) case 3, *R*=10cm.

In these three cases, as shown in Figure 6, all of the gas triangles have a similar slant angle θ while the height h of gas triangles floats substantially. The minimum height is 0.5cm and the maximum is 1.5cm. It is mainly affected by the location of the detonation wave. When two detonation waves are too close, the latter arrives shortly after the former passes by and the gas triangle has little time to be full-blown. Then, h will be small.

When the size of the chamber is increased to *R*=12cm, detonation wave behaviors become more complicated. The detonation waves do not spread in the same direction one after another. In spite of this, it does not cause disorder. The detonation waves keep a steady state and go round and round and show good periodicity.

To a significant degree rotating detonation waves' behaviors are similar in the hollow and annular RDE models, including detonation waves' properties, how the waves keep rotating, how the waves come to a steady state. Meanwhile, it is certain that waves in there two models have some differences. In order to discuss this problem, we add another two simulation cases, which are numbered cases 5 and 6. In these two cases the physical models are annular chambers with the same size as in case 1. The channel width between the outer and inner walls in case 5 is 3cm, which is the same size of gas-intake region in case 1. Case 6 has a typical annular chamber with a thin channel of 0.8 cm.

The results are shown in Figure 7. In Figure 7(a), One big detonation wave propagates inside. The detonation front strongly hits the outer wall and reflects, resulting a shock wave 2. And then, this transverse shock spreads and reflects the inner wall resulting in a shock wave 3. Since in case 5 the channel is as wide as 3 cm, which is half the radius, this reflection is quite weak. So is wave 3. In annular models with thin channels, the reflection is more violent and may happen several times. Meanwhile, in the hollow model, as shown in Fig. 11b, no remarkable reflection happens behind wave 2, because there is no wall in the hollow chamber. Moreover, in Fig. 11a there is only a big detonation wave while in Fig. 11b two small detonation waves are propagating. In previous work, one-waved and two-waved RDEs in annular chambers were worked out with different initialization setups, with one and two detonation waves, respectively. However, in this work, the ignition conditions of cases 1 and 5 are the same. Different physical models cause the difference. In the evolution from the initial to the steady state, the presence and lack of an inner wall lead to different detonation wave behaviors.

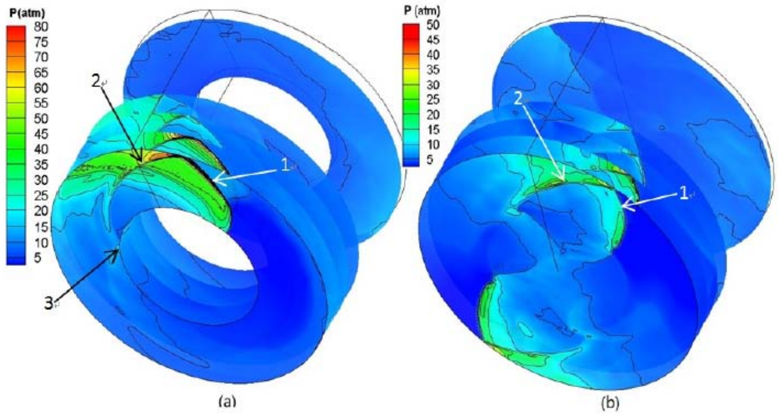

Figure 7. Comparison of pressure contours between the annular model and the hollow model on a series of slices: from Z=0 to Z=0.4L. (a) pressure contour in the annular model, (b) pressure contours in the hollow model. 1-detonation wave. 2-transverse shock resulting from detonation wave reflection. 3-shock resulting from reflection of shock 2.

Experiments[6] show that cellular structures are small near the outer wall and quite large near the inner wall. The outer wall is concave for detonation waves and its positive curvature helps strengthen the detonation. In contrast, the inner wall in the annular model is convex for detonation waves and its negative curvature weakens the detonation. The outer wall plays a role in geometrical compression while the inner wall plays a role in geometrical expansion in the annular model. The conclusion drawn from such an analysis is that the outer wall is a determining factor in the continuous rotation of detonation. That is why in this work without an inner wall, detonation waves can still rotate in the hollow combustor.

In temperature contours of the result of the hollow model we find a small region with low temperature on slice r=0.47R_{outer}. As mentioned above, the solid wall locates at the head end the inner area (r<R_{inner}). No injection nozzle exists in this region. However, here at $r=0.47R_{outer}$ there is fresh gas. The reason is that fresh gas at $r>=R_{inner}$ flows around and then spreads to region $r<R_{inner}$ because no inner wall exists in the hollow chamber. This part of the fresh gas is rapidly combusted by the hot gas in the center of the cylinder. The energy conversion is done in deflagration instead of detonation because this mass of fresh gas is not big enough to continuously sustain a rotating detonation wave. This phenomenon will affect the propulsive performance.

The propulsive parameters of the RDE such as the thrust and the fuel-based specific impulse are evaluated as follows. The thrust $\boldsymbol{F}$ of the chamber exit is obtained as

$$F = \int_{exit} [\rho u^2 + p - p_\infty] dA.$$

The fuel-based specific impulse I_{sp} is obtained as

$$I_{sp} = \frac{F}{\dot{m}_f g_0}.$$

And then these parameters in each case come to constants, respectively, and are shown in Table 1.

Table 1: Propulsive parameters of RDEs simulation cases

case	$\dot{m}_{Tot}$ (kg/s)	$\dot{m}_f$ (kg/s)	F(kN)	I_{sp}(s)
case1	3.63	0.098	6.0	6600.48
case2	6.93	0.187	13.3	7180.01
case3	11.09	0.301	21.2	7220.58
case4	19.17	0.518	37.8	7401.42
case5	3.81	0.103	7.3	7290.55

As mentioned above, physical models in cases 1-4 are hollow chambers and the model in case 5 is an annular model. It is indicated that RDEs with the hollow model can get a fuel-based specific impulse I_{sp} around 7000s. When the chamber size becomes bigger, the specific impulse presents a limited increase while the mass flow rate increases rapidly.

Since case 5 yields results of RDEs with annular chambers with the same size as the hollow chamber in case 1, we compare with case 1. We find that when their sizes are the same, their mass flow rates are quite similar but their impulses are different. RDEs with annular chambers have higher impulses than RDEs with hollow chambers. The cause may be complicated and needs further investigation. However, some causes were mentioned when we compared the annular and hollow models. On the inner boundary of the gas-intake region, a small part of the gas spreads to the region $r<R_{inner}$ and is combusted by the hot gas in the center of the cylinder in deflagration. It causes some decrease of impulse.

4 Conclusion

Considering the heating problem in an RDE with an annular chamber, we proposed an alternative model that has no inner wall and is hollow. We conducted preliminary investigation to find whether a detonation wave can continuously rotate in this RDE model. A series of numerical cases were presented. The results suggest that this new model for RDEs works. It can be used in RDEs for complete energy conversion in detonation. The fuel-based specific impulse can reach around 7000s. Bigger sizes are provided with higher impulse. Moreover, in this study, some details were discussed, such as the importance of gas triangles to detonation's stability, differences between the annular and hollow models. To a significant degree, detonation manifestations are similar in the hollow and annular models. The differences are that there is no repeated reflection of shocks in the hollow model and a little gas is ignited by the hot gas in the center of the cylinder, which causes some decrease of impulse. Meanwhile, there are still many unclear sides about it. Further researches are needed to understand this new model more penetratingly. One is what decides the number of detonation wave fronts, why there is one front in the annular chamber and two fronts in the hollow chamber while they have the same size. Another one is that why RDEs with annular chambers have a higher impulse than RDEs with hollow chambers when their sizes are the same.

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