Three Dimensional Simulation for the Effects of Fuel Injection Patterns in Rotating Detonation Engine

Liu Meng, Wang Jian-Ping
State Key Laboratory of Turbulence and Complex System, College of Engineering,

Peking University
Beijing, China

1 Introduction

Detonation is a high efficient combustion process that can release more power than normal deflagration combustion. Utilizing detonation as major combustion mode is a core purpose in many new generation engine concepts. There are a lot of researches on pulse detonation engine [1], and rotating detonation engine (RDE) has become a new important branch in detonation engine study. The concept of RDE is concise, as it is showed in Figure 1, and it has already been tested fundamentally feasible in experiments [2]. A lot of simulation works [2] have also done to investigate the flow field and other detailed information within the combustion chamber. On most occasions, two dimensional simulation with fine grids are the main procedures. The engine can be simulated in a two dimensional way, owing to that the distance between the inner wall and outer wall of combustion chamber is very small. However, the threshold of "small distance" is vague, and most experimental design of RDE cannot guarantee the reactions in the chamber may go uniformly in radius direction. And in most simulation cases, the boundary conditions of the fuel injection wall are normalized as a combination of solid wall and inlet. Three dimensional model and two different fuel injection patterns are used to get more information of detonation wave movement during the initiation periods. The results suggest that the injection patterns may change the correlations of shockwaves and combustion layers, and significantly influence the possibility of high efficient detonation combustion.

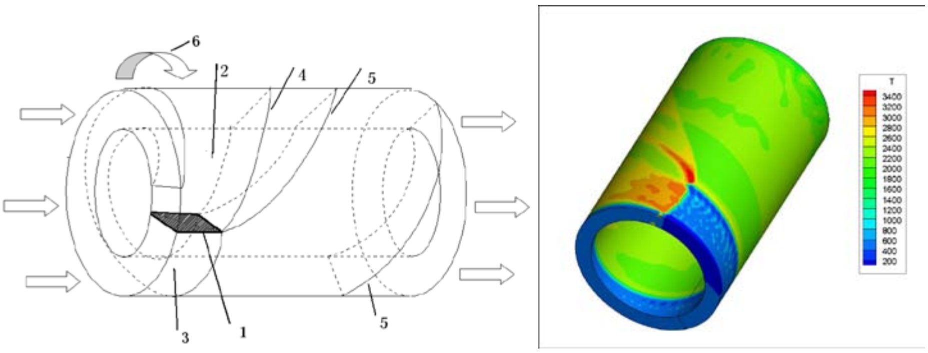

Figure 1. Scheme of RDE and 3D simulation result in a normalized injection pattern

Correspondence to: sodynamic@163.com

2 Numerical methods

The combustible mixture is air and hydrogen, and it is simulated by one-step chemical kinetic model. The governing equations are the three-dimensional Euler equations. Flux terms are solved by using the so-called monotonicity-preserving weighted essentially non-oscillatory scheme (WENO), and time integration is performed by using the third-order total variation diminishing Runge-Kutta method.

The grid in this simulation is $32 \times 256 \times 128$, and the grid unit size is about 1mm. The inner radius of the basic model is 3cm, and the outer radius is 4cm. This grid is too coarse to show precised structure of detonation cells, but it is good enough to capture detonation phenomenon. As the case showed in Figure 1, the average speed of detonation wave is 1800m/s, which is quite similar to the theoretical CJ hydrogen-air detonation speed 1980m/s.

The boundary conditions of the fuel injection wall are showed in Figure 2. The black parts denote the area with inlet , and the white parts denote complete solid wall. In this paper we refer the pattern on the left as round gap, and the right one as angular intervals. The inlet area is set as usual RDE simulation boundary conditions, which the characters of the flow are based on the pressure on the injection wall.

All the cases are ignited by a one dimensional CJ detonation wave at one point in the chamber.

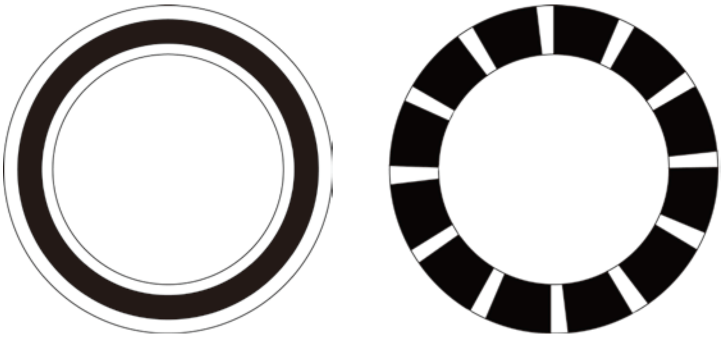

Figure 2. Two patterns of fuel injection.

3 Results and discussion

3.1 Round gap

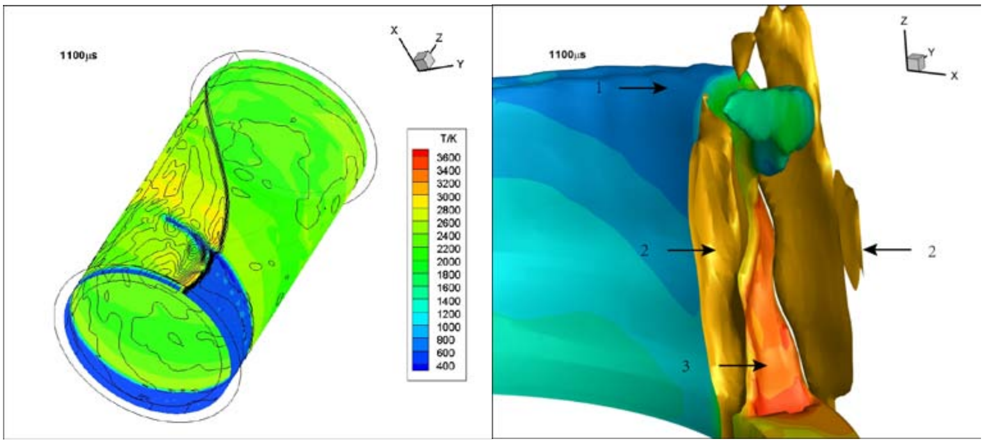

Figure 3. The temperature contour for pattern round gap (85%) at the time of 1100 μs

In the first case, the total pressure of the fresh combustible mixture is 30atm, and the inlet area takes 85% of the whole injection wall. As shown in Figure 3, the left picture is a radial middle slice at in the chamber. The color flood denotes the temperature, and the lines denote the pressure. The picture on the right denotes the 3D structure at the detonation wave section. Number 1 points to the bulk of fresh mixture. Number 2 points to a yellow isotemperature surface of 3100K, and Number 3 points to the red shockwave front. It shows that the most intense combustion is not behind the shockwave front, but on the two sides. The heat released from these two combustion layers pushes the shockwave and compresses the unburned mixture.

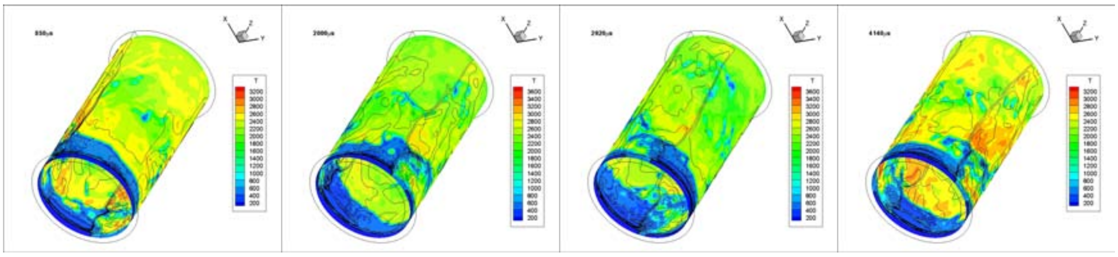

Figure 4. Instability of round gap pattern (73%)

Figure 4 shows another case which reduces the round gap proportion to 73%, but remains the same total pressure. It shows the contours at time of 850 μs , 2000 μs , 2920 μs , and 4140 μs in order. Two immature wave heads can be seen in these 4 pictures, and the directions are changed repeatedly.

3.2 Angular intervals

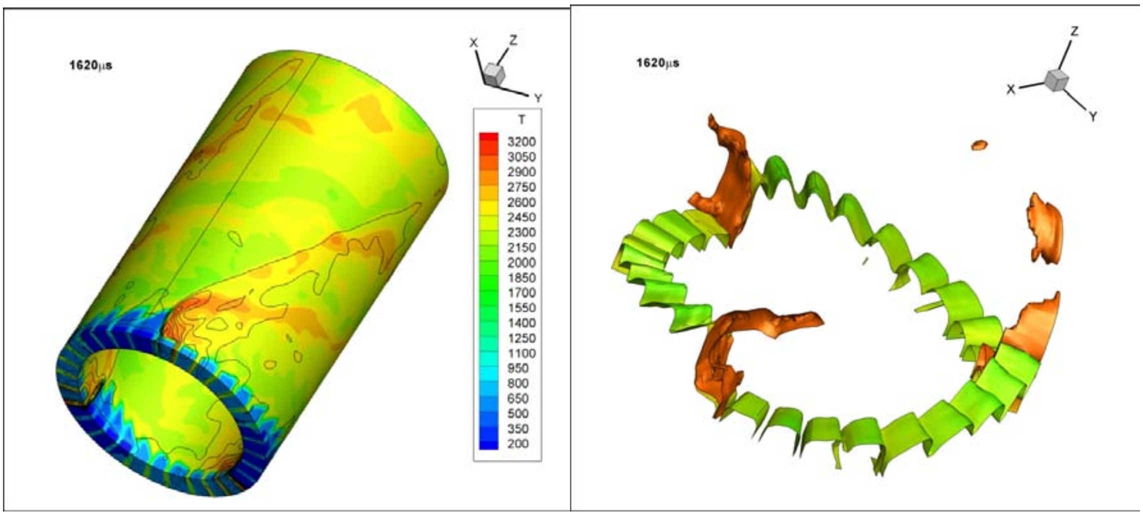

Figure 5. The temperature contour for pattern angular intervals at the time of 1620 μs

The total pressure of fresh mixture is 30 atm and the inlet area proportion is 75% in Figure 5. The figure shows that when the combustion come to stable at 1620 μs , three similar detonation waves travel in same direction. The figure on the right shows the isotemperature surface of the flow field. The distribution of three detonation fronts and the injection of fresh mixture are clearly depicted.

Figure 6 shows the process of the formation of the three detonation waves. From the very beginning the mixture is ignited by a detonation wave, and forced to travel in one direction. In the following reaction the collisions of detonation waves cause the variation of the total number of waves. In the picture, the number and the directions of the waves are 1 front clockwise, 2 fronts in both direction, 4 fronts counterclockwise, and 3 fronts counterclockwise, respectively.

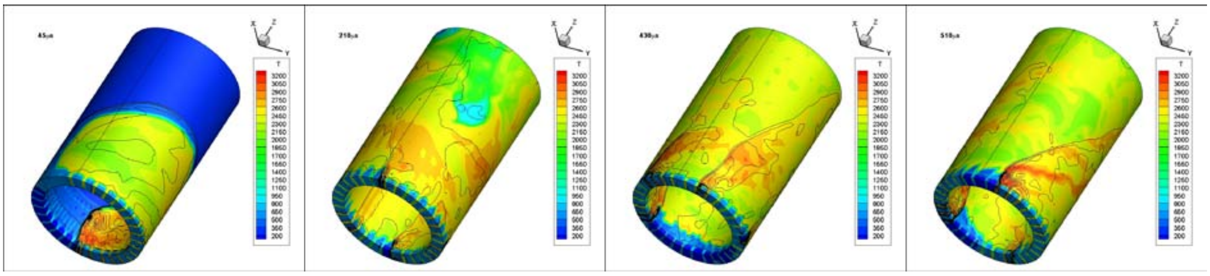

Figure 6. Variation of numbers and directions of detonation waves after ignition

The two patterns above show that detonation combustion supply the power for the shockwave, but the combustion layer does not need to go behind the shockwave front. The combustion products can accelerate the ignition, but it will also exhaust the strength of shockwave. Combustion products may also be an important reason for multiple wave fronts. The stable detonation wave may have different direction from the ignition detonation.

The above case alone is not sufficient to find out the relations between the shockwave numbers and the injection patterns. There are more numerical investigation to offer more solid conclusion.

First of all, we do two more computations using the same size of combustion chamber, and same ignition properties, except the grid size is narrowed to 0.5mm and 0.25mm. The average speed of the shockwave front declines to 1480m/s, because detonation is not sufficiently maintained during the travelling.

Secondly, we use 0.5mm grids, but we enlarge the chamber inner radius to 6cm and 12cm, and the chamber still keeps 1cm space between the inner wall and the outer wall. There are four ignition places when time is 0. When the combustion becomes steady, as shown in Figure 7, the number of shockwave fronts increase to 4 and 8.

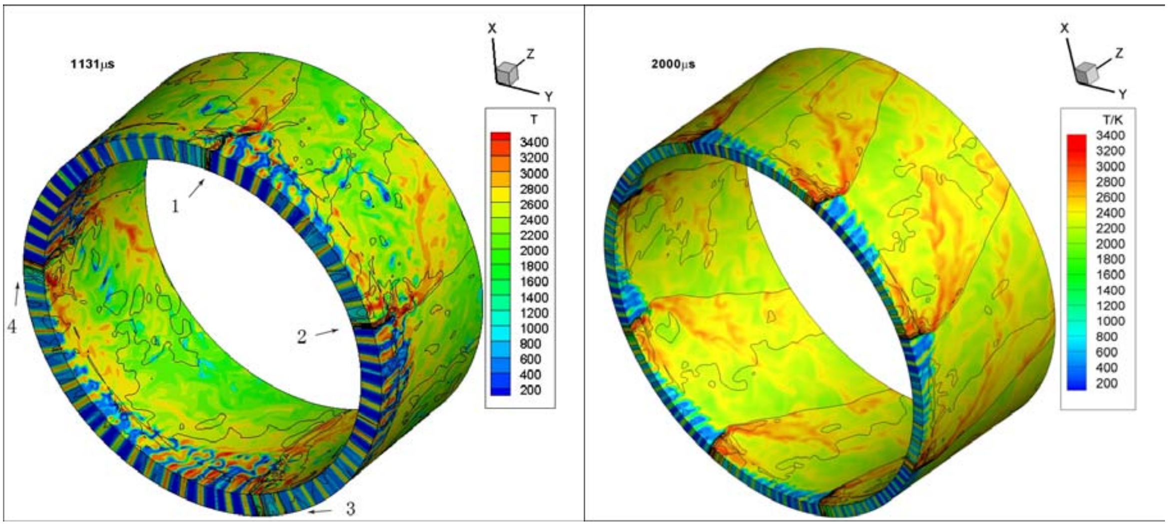

Figure 7. There are 4 shockwave fronts when the inner radius is 6cm (left), and there are 8 shockwave fronts when the inner radius is 12cm (right). The numbers in the picture indicate the shockwave fronts positions.

Finally, we use the 6cm inner radius chamber to simulate two other cases while ignition places are 2 and 8 each. All three cases are finally converge to 4 shockwave fronts, as shown in Figure 8. Obviously the 4 fronts are not located evenly in every case, and the shapes of the air distribution are irregular. This is because the injection pattern makes the whole combustion chamber a dynamic uneven environment.

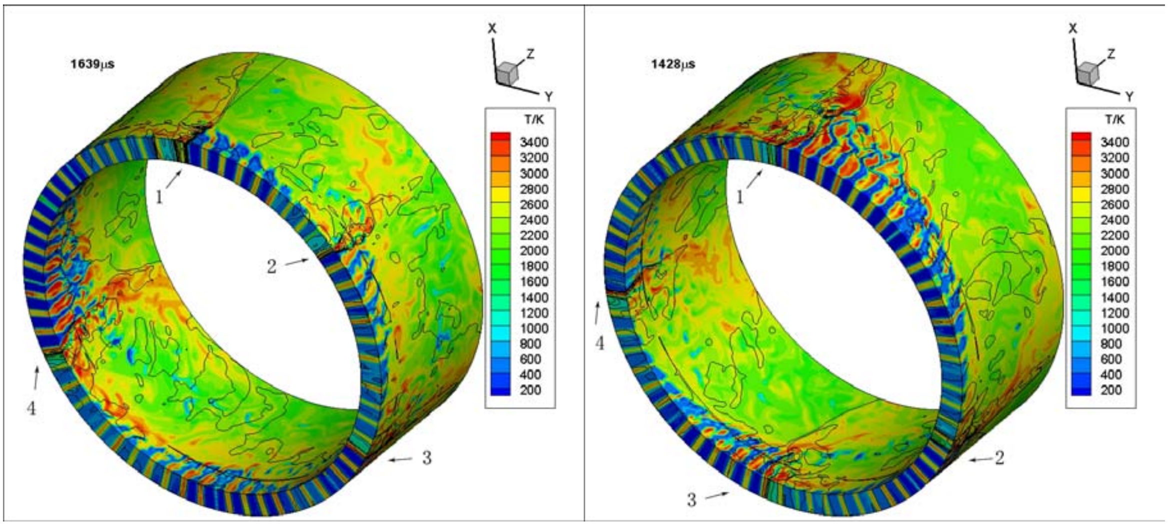

Figure 8. 6cm inner radius chamber cases with 2 ignition places (left) and 8 ignition places (right). The numbers in the picture indicate the shockwave fronts positions.

4 Conclusion

This study shows that different fuel injection pattern may change the wave's shape and distribution. Proper utilization of combustion products may improve the detonation performance. And the multiple wave fronts comply with the experimental observation. According to the numerical results, the total number of shockwave fronts has inherent relationships with the pattern of the injection and the size of the chamber. Three dimensional simulation is proved to be a better analysis to investigate various engine concepts.

References

[1] Roy G D, Frolov S M, Borisov A A, et al. Pulse detonation propulsion: challenges, current status, and future perspective. Progress in Energy and Combustion Science. 30: 545-672, 2004.

[2] K. Kailasanath. (2011). The Rotating-Detonation-Wave Engine Concept: A Brief Status report. 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition.