Effect of Expansion Outlet on Continuous Rotating Detonation Combustor

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1 Introduction

The CRDC (continuously rotating detonation combustor) is a new type of combustor based on detonation combustion, which is compact compared to conventional isobaric combustor and greatly attracts the researchers' attention due to its unique pressure gain performance. In the future, the application of detonation combustor in actual production should face the coupling problem with other components. In recent years, coupling experiments between CRDC and other components have been carried out in many countries [4-9], which confirm the feasibility of matching the CRDC to other parts of the engine. However, there is still little research work on the numerical simulation of such problems. Considering the unstable operating environment of CRDC, there is extreme pressure and temperature fluctuations, which means that the integrated coupling with turbine faces severe gas, heat and structural challenges [10-11]. In this paper, the numerical simulation of CRDC with variable cross-section outlet is carried out. This study is based on the consideration of coupling the relatively small-sized CRDC with turbine, and the expansion outlet of combustor is designed. On this basis, the effects of the pressure gain performance and flow field parameters of the detonation combustor are studied.

2 Numerical Model and Method

The three-dimensional geometric model of the continuous CRDC with the expansion outlet is shown in Fig. 1. The prototype CRDC according to the size of a micro-turbine combustor has an outer radius of 137.4 mm, an inner radius of 117.4 mm and the seam width of 20mm [12][13]. A methane-air premixed gas with an equivalent ratio of one is directly injected into the combustor without complicated head inlet structure. And to initiate detonation in the annular combustor channel, a virtual initiator was used to generate the Chapman–Jouquet (CJ) ignition kernel in the right direction. Figure 2 shows the computational domain grid. In order to better simulate the effects of the expansion segment, it is properly mesh-encrypted

The Fluent solver is used to perform numerical simulation based on the assumption of compressible ideal

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gas. The time convection term is solved by AUMS, the explicit time equation based density is the 4-stages Runge-Kutta, and the 2-stagesr implicit is the 3-stages Runge-Kutta. The stratified flow rate model was selected for laminar finite-rate model, and the reaction rate constant was calculated by the Arrhenius formula.

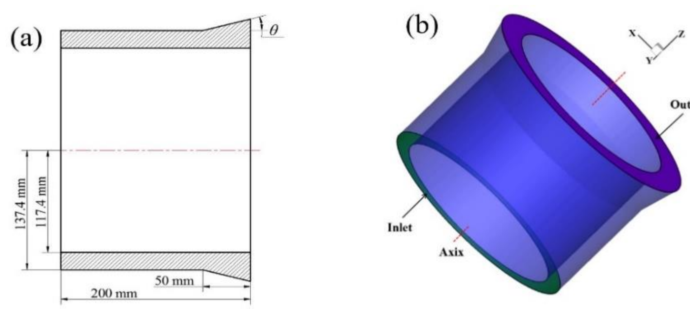


Figure 1. (a)The profile of geometric model Geometric model; (b) Geometric model

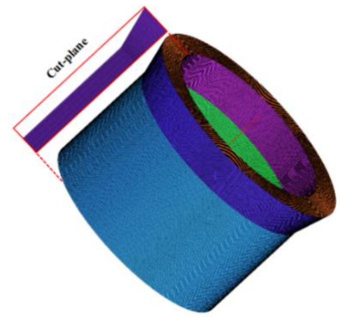
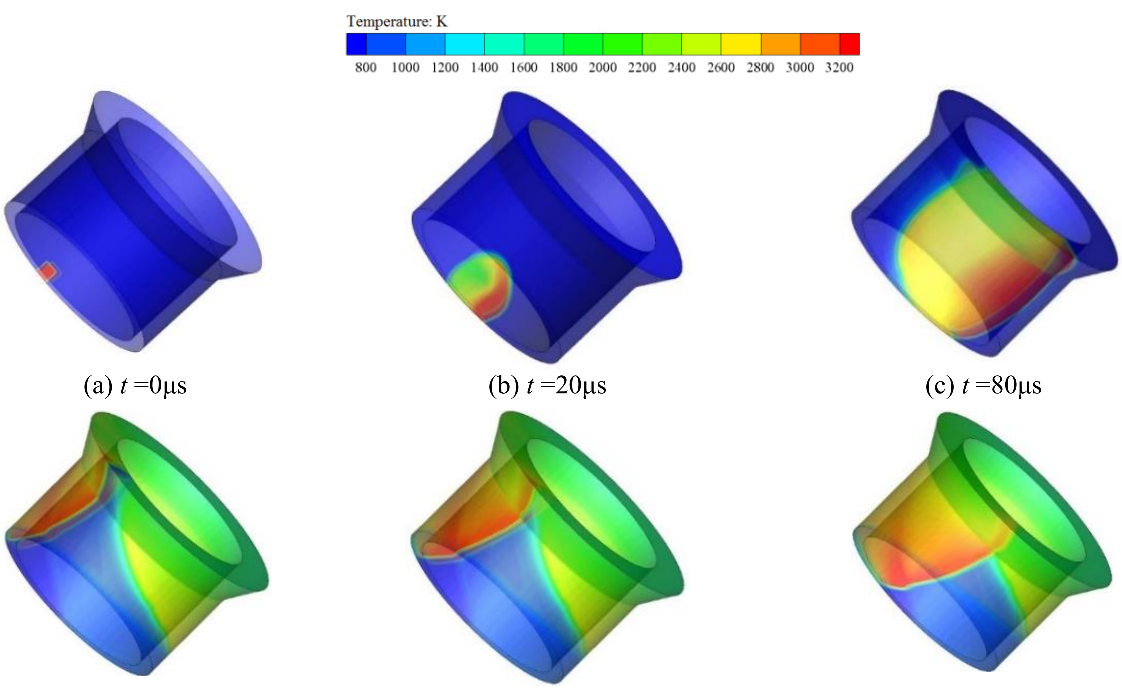


Figure 2. Computational domain grid

3 Results and Discussions



(a) t =0μs (b) t =20μs (c) t =80μs

(d) t =440μs (e) t =460μs (f) t =500μs

Figure 3. Evolution of the flow field in combustor with expansion outlet

Figure 3 shows several typical stages of the evolution of the flow field during the propagation from ignition to stable detonation in a CRDC with a expansion outlet (example θ = 30 °). As shown in Fig. 3(a), at the initial moment, the direct initiation of detonation accurs in CRDC.After the ignition, when t=20μs, it can be found that the flame front is formed in the same direction as the propagration direction. At the same time, there is an uncoupling pressure front and slow flame front with opposite direction propagation directions. When t = 80 μs, the detonation wave develops further in the combustor, while the reverse pressure wave velocity and intensity are weak. When t=440μs, the detonation wave meets the opposite direction propagating weak pressure wave, and the combustion field enters a transient unstable phase during the collision. Then the detonation wave then meets with the reverse flame-retardant flame front. At this time, the detonation wave approaches the outlet side and collides with the flame-retardant flame front. After that, it degenerates into oblique shock wave, and the oblique shock wave falls at the expansion section of the combustor. The detonation wave near the inlet continues to propagate forward with the newly injected premixed gas. Finally, after t=500μs, the detonation wave achieves stable self-sustaining propagation in the expansion outlet combustor.

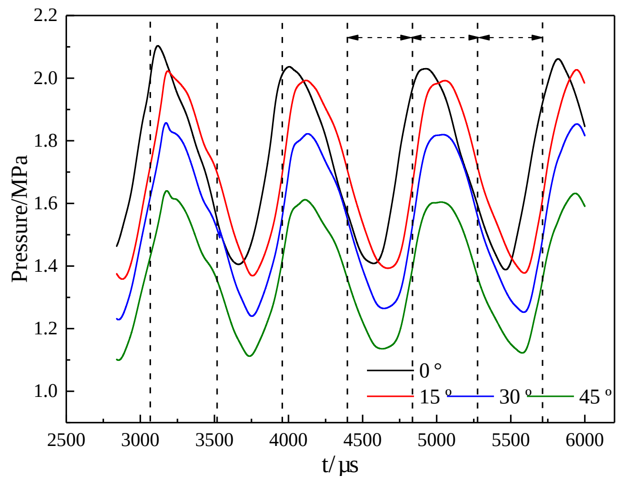


Figure 4.Average total pressure curve of outlet in four cases

Table1. Pressure ratio of compressor in four cases

θ /°	0	15	30	45
π	1.42706	1.392211	1.270159	1.12948

Based on the feasibility of achieving stable self-sustained propagation of continuous rotating detonation waves in the expansion outlet combustor, the expansion angles θ are respectively 15 °, 30 ° and 45 °, and compared with the case where θ = 0 °. Figure 4 shows the average outlet pressure curve for four cases after 10 cycles of detonation wave propagation, and Table 1 shows the corresponding CRDC pressure ratio of compressor. Combining these two aspects, it can be found that the appearance of the expansion outlet will reduce the pressure gain performance, and it will gradually decrease as the expansion angle increases. This means that the expansion of the outlet will reduce the pressure gain performance of the CRDC to a certain extent, and in order to study the reasons for the decrease of compression performance, it is necessary to study the changes of other flow field parameters.

Figure 5 shows the distribution of static temperature along the circumferential direction in the outlet section under four cases. It is found that the appearance of the expansion outlet will result in a large decrease in the static temperature of the outlet, and the greater the expansion angle, the lower the static temperature. The detonation peak temperature decreases from 3072.8K at θ=0° to 2012.7K at θ=45°, which reduces to a degree of 34.5%.

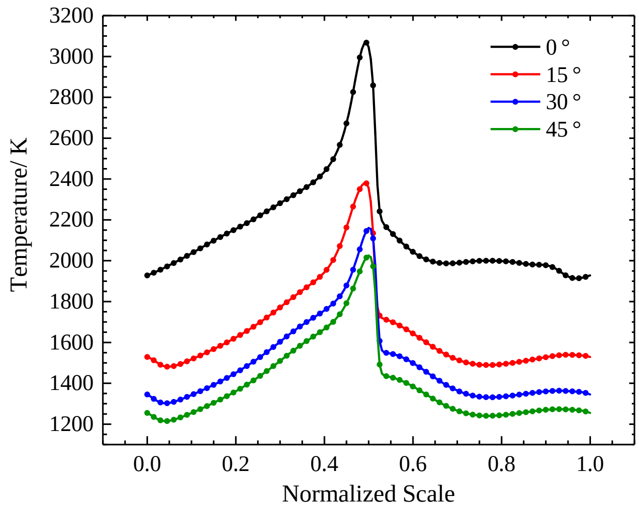


Figure 5.The outlet circumferential static temperature distribution of the middle meridian

Since the total temperature is constant, the static temperature in the expansion outlet is related to the outlet velocity. From figure 6, it can be seen that the static temperature decreases gradually, and the outlet velocity increases when there is expansion. The changes of the static temperature and the exit velocity are in accordance with the basic law of the isothermal process.

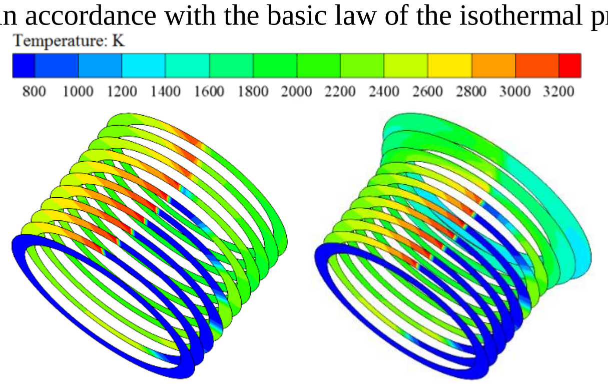


Figure 6. Static temperature distribution of each section with and without expansion structure

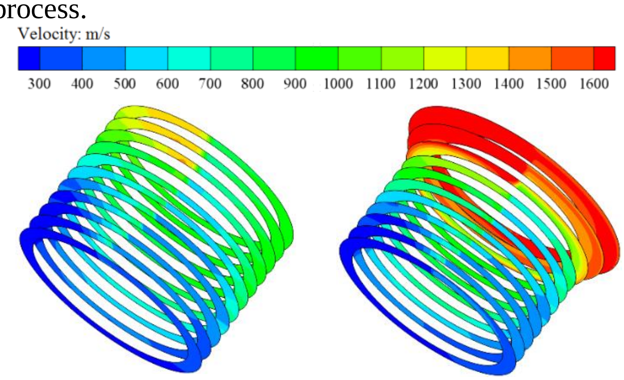


Figure 7. Outlet velocity distribution of each section with and without expansion structure

In order to investigate the variation of flow field parameters in combustor with different outlet expansion angles, the circumferential static pressure in expansion outlet was compared. As shown in figure 8, the expansion outlet reduces the outlet static pressure significantly, and the circumferential static pressure decreases with the increasing of the expansion angle. Compared with the circumferential static temperature distribution of the expansion outlet, the change of the outlet static pressure is more sensitive to the expansion structure, in contrast, the expansion angle seems to have no obvious effect on the distribution of the outlet static pressure.

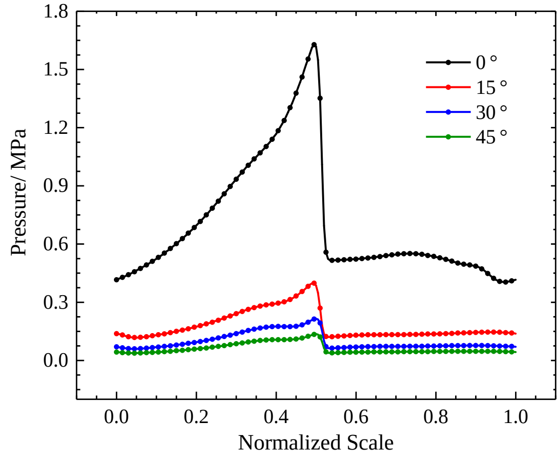


Figure 8. The outlet circumferential static pressure distribution of the middle meridian

Figure 9 shows the static pressure distribution of each section in CRDC, which is the static pressure distribution with and without expansion structure. It can be found that the static pressure with the expansion section is significantly reduced. Figure 10 shows the entropy distribution of CRDC with and without expansion outlet. It can be found that the entropy increase in the expansion section is obviously larger, that is, the entropy increases in the region caused by the expansion, which means that the loss is obviously increased. It leads to the reduction of the pressure gain performance of the CRDC, ultimately.

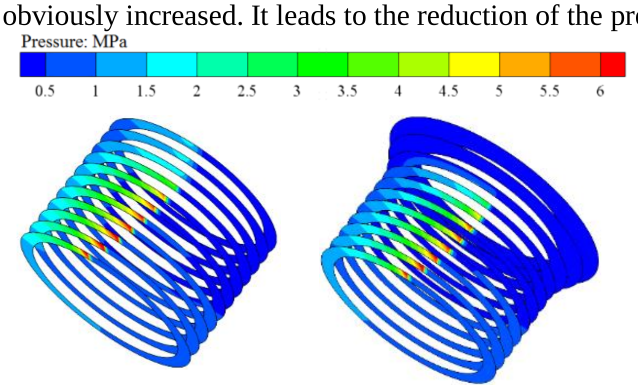


Figure 9. Static pressure distribution of each section with and without expansion structure

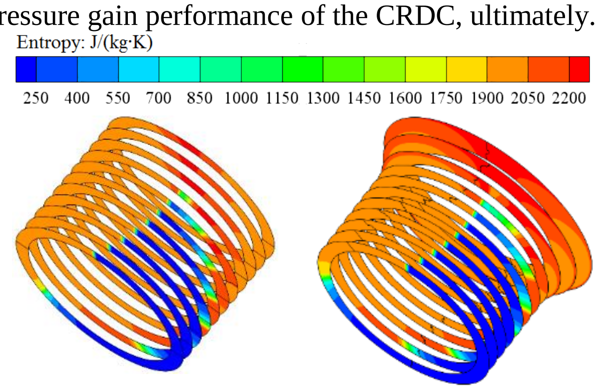


Figure 10. Entropy distribution of each section with and without expansion structure

4 Conclusions

In this paper, the stable propagation of continuously rotating detonation wave in the combustor with expansion outlet is realized, and three different expansion angles are simulated. It is found that the expansion outlet can reduce the pressure ratio of the CRDC. And with the expansion angle of the outlet increasing, the pressure ratio of the CRDC decreases, while still maintain s certain pressure gain performance. The static temperature of the outlet decreases, and the axial velocity of the outlet increases. To realize the coupling between the CRDC and the turbine, the outlet of the combustion chamber is designed as an expansion structure. Although the pressure gain performance of the CRDC is slightly reduced, the static temperature in the outlet of the combustor is reduced, which results in the decrease of the thermal stress at the outlet, at the same time, the axial velocity of the outlet increases, which seems to provide some reference for the design of ramjet engine.

Acknowledgments

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