

Numerical Studies on the Stability of Rotating Detonation Engines

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1 Introduction

Due to nearly isochoric combustion process, detonation-based engines have higher performance than conventional isobaric-combustion-based engines and have been desirable for many years. Rotating Detonation Engine (RDE) is a new-concept engine of such kind propulsion systems and has received worldwide attention in recent years.

The basic concept of RDE was introduced by Voitsekhovskii[1] in the 1960s, and he experimentally achieved a short-lived continuous detonation in a circular tube, using premixed acetylene and ethylene. The feasibility of RDE has been experimentally shown at the Lavrentyev Institute of Hydrodynamics (LIH)[2]. And in recent years, Wolanski[3], Wang[4], Shank[5], Naour[6] et al. have also conduct experiments with various mixtures, mixture compositions, initial pressures and mass flow rates in different setups. However, experimental research, focusing on mapping out operational regimes for different configurations, has provided little information on the flow field within the detonation channel. And this shortcoming has been addressed by numerical investigation.

Since the early two-dimensional simulation of rotating detonation performed by Zhdan et al.[7], the overall description of the flow field within an RDE combustion and its propulsive performance have been clarified by several groups[8-10] numerically. For example, in our group, Shao et al.[11-12] have done three-dimensional simulations of RDE and discussed several key issues, including the fuel injection limit, thrust performance, and nozzle effects. These previous simulations focus on the characteristic of stable detonations, which are established after a time period since ignition, and neglect the ignition process. However, ignition is of great importance for RDE's practice use. And the main purpose of this paper is to discuss the effects of different ignition methods on the formation of rotating detonation, the features of formed rotating detonation and the detonable limits for stable RDE, focusing on the stability of RDE.

2 Numerical Method

In our simulation, a one-step chemical reaction model is used and three-dimensional Euler equations in generalized coordinates are used as governing equations:

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

The detailed description of above equation and numerical methods are given in Ref [11]. In our simulation, the average grid size is 0.2mm. The thermochemical model and computation scheme have been validated for some simple one-dimensional and three-dimensional test cases with grid size of 0.1mm, 0.2mm and 0.4mm, respectively. The results are shown in Figure 1 and 2. The detailed information is discussed in Ref [12]. The above comparison proves the numerical convergence and grid dependency.

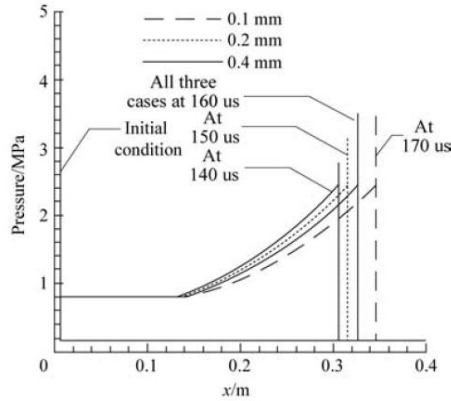


Figure 1. One-dimensional detonation wave

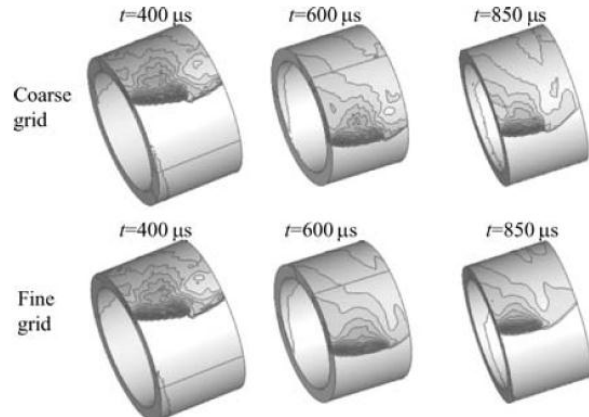


Figure 2. Three-dimensional rotating detonation wave

3 Result and Discussion

The flow-field is initially filled with quiescent air at 1atm and 300 K, except for the head wall region where premixed fuel mixture (hydrogen and air) fills. For the initial ignition condition, 1D numerical results of detonation are placed at the head wall region. They are placed along the axial direction for the same distance as fuel mixture. Figure 3 shows the two different ignition methods: a 1D C-J detonation wave or two central symmetric 1D C-J detonation waves. In the numerical simulation, the environment pressure is 0.5atm.

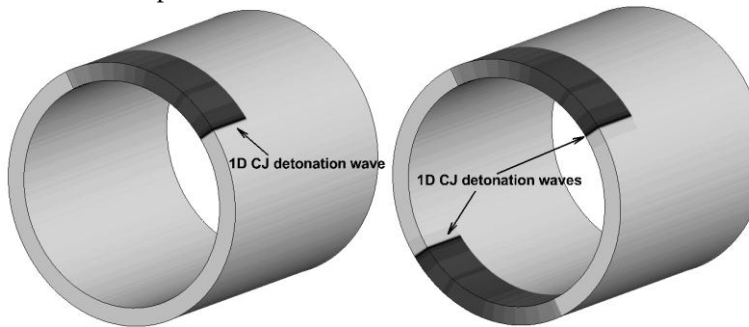


Figure 3. Ignition methods. Left: one-waved. Right: two-waved.

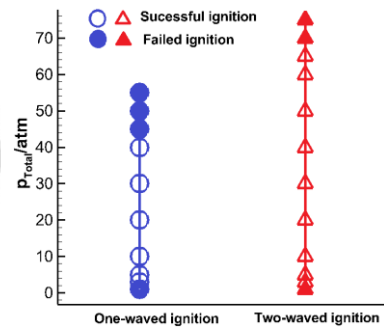


Figure 4. Operating space

3.1 Operating space and ignition process

For RDE, one kind of “pressure-gain” combustion systems, pressure change is one important factor for determining its performance. In this part, the total pressure (p_{total}) for inlet Laval-nozzles is varied to see its effects on the ignition of RDE.

Figure 4 shows the RDE operating space for the two ignition methods. For one-waved detonation, rotating detonation can be achieved when the inlet stagnation pressure are around 5~40 atm. The successful range of p_{total} for two-waved detonation is around 3~65atm, which is wider.

For both one-waved ignition and two-waved ignition, the ignition process and failed ignition mechanism are similar. After ignition, the starting 1D CJ detonation wave propagates clockwise and initiates the fuel mixture at the head wall region. At the same time, the burnt gas of 1D CJ detonation wave, which is of high temperature and pressure, also combust the fuel mixture and a counter-clockwise running deflagration wave forms. The two counter-rotating waves will collide with each other inevitably and the pre-existing fuel mixture is completely burnt at the time of collision. When p_{total} is under the lower limit, only a little fresh fuel mixture can be injected into the chamber and the injecting area is far from the detonation wave and deflagration wave. Without fuel mixture ahead, detonation could not persist after collision and the ignition fails. If the inlet total pressure is higher, fuel mixture can be injected into the chamber right behind the deflagration wave. After collision, the two waves coalesce into one detonation wave. When the inlet total pressures are above the upper limit, taking the case of two-waved ignition for example, Figure 5 shows the ignition process. The high pressure could push fresh fuel into the chamber across the whole injecting area at the head wall before collision. The burnt products of high temperature after collision would detonate fresh mixture and generate new detonation waves (indicated by 2, 4). The new generated detonation waves propagate against the direction where the corresponding pre-existing detonation waves move (indicated by 1, 3). Afterwards the four detonation waves become stronger, and no fresh gas could be injected into the chamber right after them. Therefore, when the nearest counter-rotating detonation waves (2 with 3, and 1 with 4) collide with each other, they cease denoting altogether. At this moment, the ignition of rotating detonation waves fails.

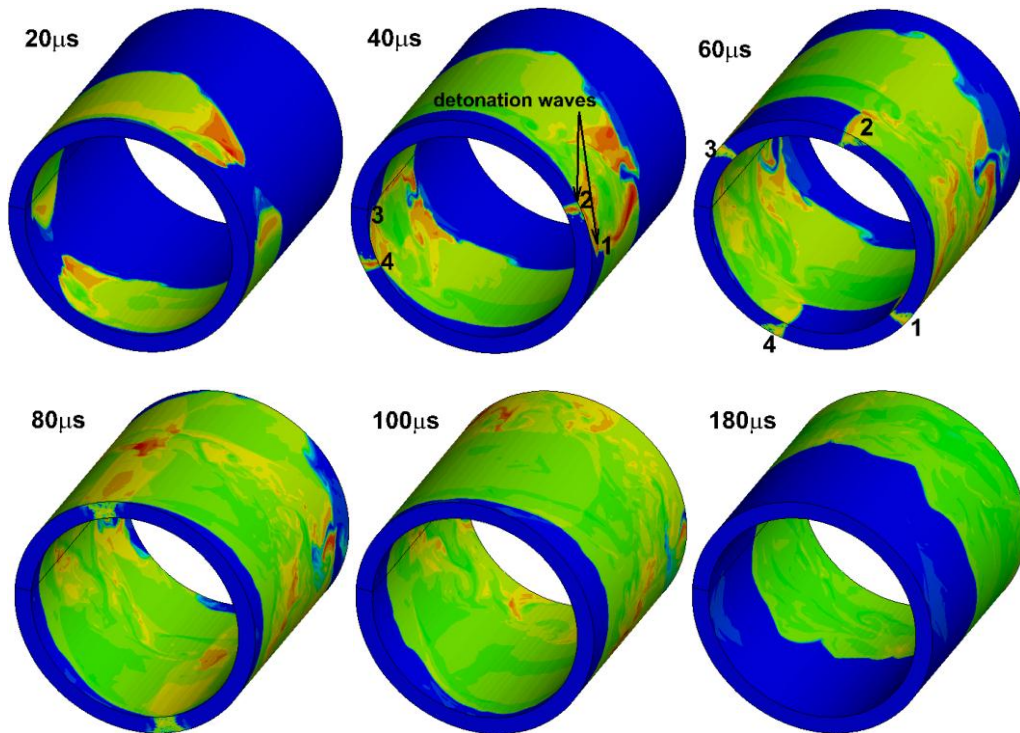


Figure 5. Ignition process for two-waved method when p_{total} is 70atm (temperature range is 600~3600K)

3.2 Sample solution

Figure 4 shows the temperature of the flow field inside the annular chamber at 1400μs when p_{total} is 30atm. For both one-waved RDE and two-waved RDE, detonation waves have propagated stably at this time. The overall flow fields present the typical structures, including the continuously rotating detonation wave, the injected fresh mixture layer, the oblique shock wave, the contact surface, and the

burnt products. The obvious differences between the two kinds of RDEs are the height of detonation waves and the strength of oblique shock waves and detonation waves.

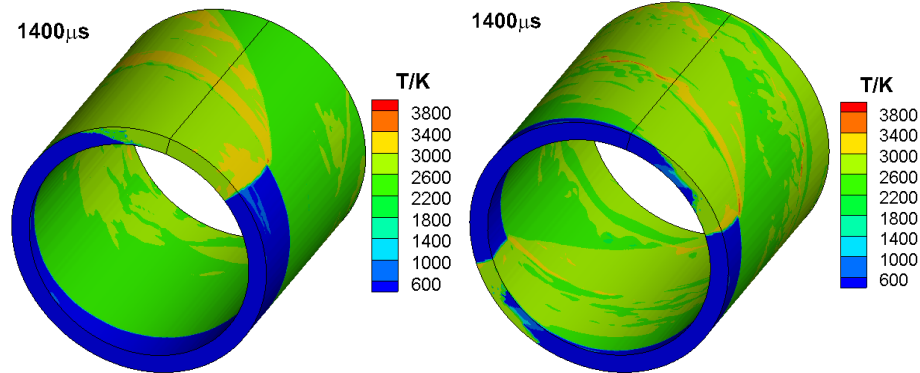
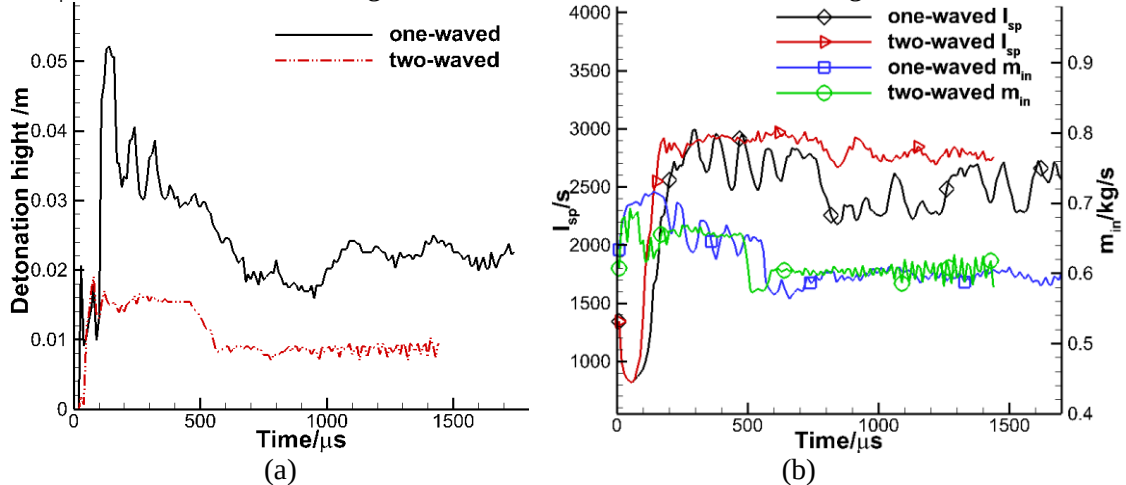


Figure 6. Temperature distribution when p_{total} is 30atm. Left: one-waved RDE. Right: two-waved RDE.

In Figure 7 we compare the detonation height, propulsive performance and other aspects of one-waved RDE with that of two-waved RDE and trace them from ignition. It can be seen that, for both one-waved and two-waved detonation, the rotating detonation wave forms at about $200\mu\text{s}$ and becomes comparatively stable at $600\mu\text{s}$. Generally, the parameters of two-waved RDE in the figure 5 have a smaller oscillation than that of one-waved RDE, showing better stability performance.

When stable, the flow mass rates m_{in} of the two RDEs approach almost the same, though the detonation height of one-waved RDE is more than twice as that of two-waved RDE. From figure 5(a) and (c), it can be found that the variation tendency of averaged pressure ahead of detonation waves (p_{aver}) over ignition time goes against with that of detonation height. The strength of detonation waves to some extent has a linear growth with the pressure of fuel mixture ahead of it. Therefore, the variation tendency of averaged pressure at the inlet plane, as well as that at the outlet plane, goes with the change of the injected fuel mixture's pressure, as shown in figure 5(d). Compared with one-waved RDE, the higher pressure of injected fuel mixture leads to stronger detonation waves in the two-waved RDE. The two detonation waves can burn the fuel mixture more quickly and reduce the possibility of deflagration of the fuel mixture. The two reasons above can explain why the fuel-based specific impulse I_{sp} of two-waved RDE is larger than that of one-waved RDE in average in this case.



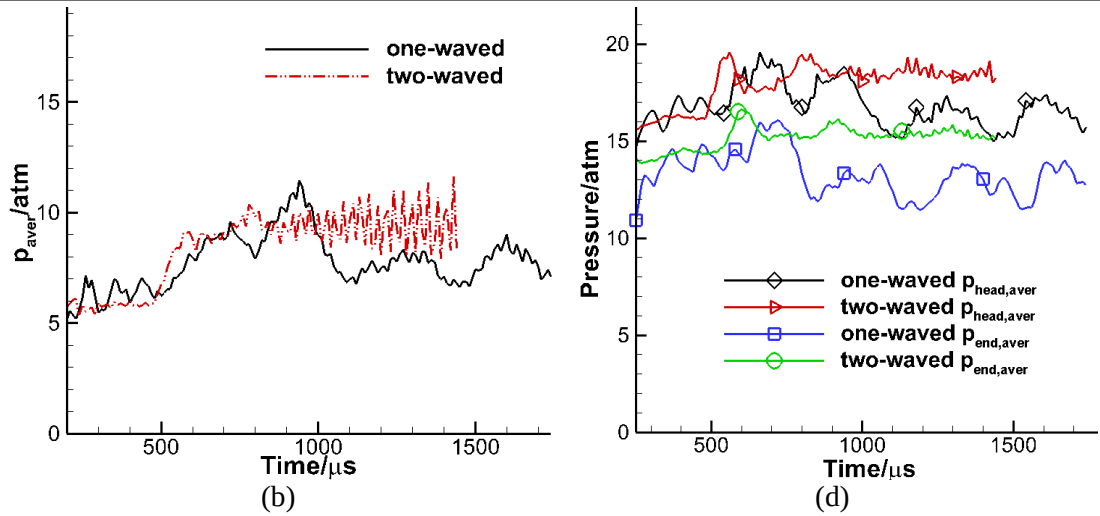


Figure 7. Comparison between one-waved RDE and two-waved RDE. (a) Detonation height vs. ignition time. (b) Mass flow rate and fuel-based specific impulse vs. ignition time. (c) Averaged pressure ahead of detonation wave vs. ignition time. (d) Averaged pressure at the inlet and outlet plane vs. ignition time

3.3 Detonable limits for stable RDE

In two-waved RDE, p_{total} is changed to see RDE's detonable limits when the whole flow field becomes stable and the results are shown in the figure 8. From the figure, it can be seen that the upper limits of stable RDE could be very high. For example, the stable rotating detonation of 30atm could endure the transformation to 90 atm. As for the lower limits, the results are very interesting. For example, when p_{total} is dropped from 30atm to 5atm, detonation waves could not persist. However, when p_{total} is first dropped to 10atm, the transformed RDE could quickly regain stable running state. In this case, the transformed RDE propagate 400 μs before stable, as shown in the figure 9, at this moment rotating detonation waves have already run about 4 circles. Then p_{total} is decreased to 5atm. At this time, transformed RDE could continue. Therefore, a short time transition (30atm-10atm for 400 μs) could lower the low limits of stable RDE. If the p_{total} is continued to drop, for example, from 5atm to 3atm and then to 2atm, the transformed RDE could still be successful. However, p_{total} decrease from 3atm to 1atm, the transformed RDE fails. The reason is properly that 1atm is too close to the back pressure 0.5atm. From most of these cases, if the changed p_{total} is larger than the previous pressure of fuel mixture ahead the detonation wave, meaning that the fuel mixture could still be injected in, the transformation would be successful, except for the case that the changed p_{total} is too close to the back pressure. For specific range or optimal transition, more cases should be studied.

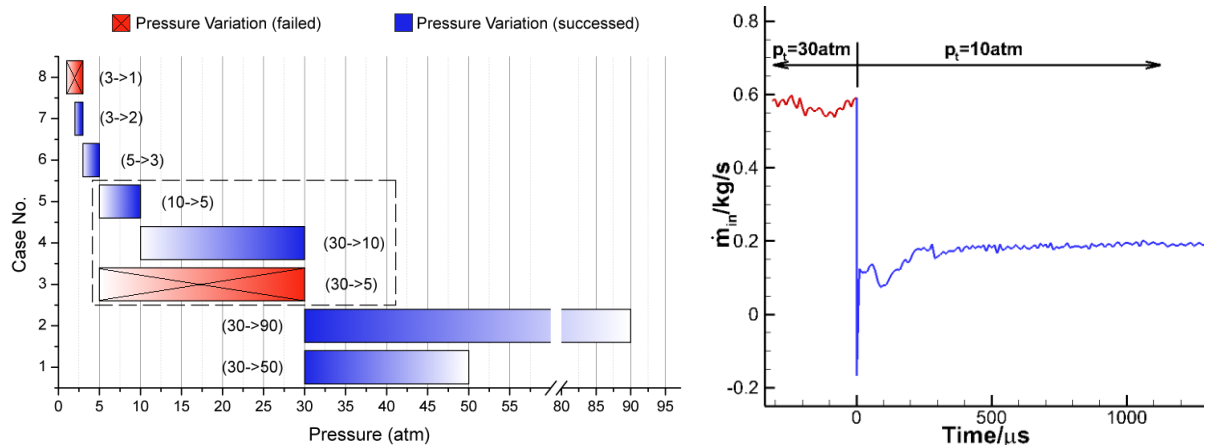


Figure 8. Detonable limits for stable RDE. Figure 9. Mass flow rate after p_{total} is changed from 30 to 10atm.

4 Conclusions

From the ignition process, the effects of ignition methods, the features of formed rotating detonation waves and also other aspects, RDE is introduced in this article and the follow conclusions are obtained:

- (a) The successful ignition range of inlet total pressure is wider for two-waved ignition than that for one-waved ignition. And formed two-waved RDE is more stable than that of one-waved RDE, for the detonation height of two-waved RDE is smaller and varies less than that of one-waved RDE.
- (b) Stable RDE could endure large upwards-transformation of p_{total} , and the valve of downwards-transformed p_{total} should be larger than the pressure of previously existing fuel mixture ahead of the detonation wave. And a short time transition could enlarge the range of successful transformation.

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