Numerical Investigation on Multi-Wave Propagation Mode of Rotating Detonation Waves

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1 Introduction

A supersonic detonation compresses the premixed reactants using a leading shock to achieve spontaneous ignition and self-sustained propagation. In recent years, detonation-based combustion has received increased interest because the thermodynamic efficiency is higher than traditional deflagration-based combustion system. One of the high speed propulsion concepts is based on rotating detonation wave (RDW), which derives to the Rotating Detonation Waves Engines (RDE). There have been significant progress of rotating detonation waves beginning with theoretical analyses, numerical simulations and experimental studies over the past few years. The detailed review of the physical flow process through the annular channel of RDEs have been studied here [1-4]. This work [5] reviewed the current status of experimental research of continuous detonation of fuel-air (C_2H_2-air, H_2-air, and CO/H_2-air) mixtures in annular combustors, which provide the effect of fuel-oxidizer compositions and combustor geometric parameters on the multi-waves and the total pressure of combustion products. However, the formation mechanism of multiple waves with different stagnation temperature and rotating detonation initiation pattern is still not clear. These characteristics are significant to understand the RDW dynamics and performance of the rotating detonation propulsion system. Motivated by these considerations, the two dimensional RDW flow structures are investigated via numerical simulations based on the reactive Euler equations. The focus of this study is the effect of inflow stagnation temperature, heat release rate and initiation on the wavelet pattern of RDW.

2 Numerical methods and physical model

A schematic of a two dimensional initial flow flied is shown in Fig. 1. The combustion or detonation chamber is usually "unrolled" to two dimensions for the radial dimension is typically small compared to the azimuthal and axial dimension, there is generally little variation radially within the entire flow. The ignition zone is set to Chapman-Jouguet (C-J) detonation wave, which is obtained from an opening straight channel. And three ignition zones (see Fig. 1, i.e., Z1: $L_1 \times L_2$=48×150; Z2: $L_1 \times L_2$=192×150; Z3: $L_1 \times L_2$=192×250), with different initiation pattern, are chosen at to investigate the possibility of multi-pattern of rotating detonation waves in chamber.

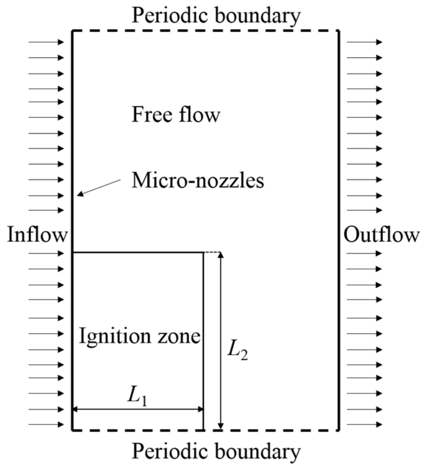

Figure 1. Schematic of an initiation of rotating detonation waves

The premixed Hydrogen-Air mixtures are injected through the left boundary, which is assumed to the inlet injection plane consisting of lots of micro-nozzles. The inflow parameters at the inlet are computed according to the stagnation pressure/temperature, i.e. p_t and T_t, and the pressure p_w near the inlet injection plane [6]. The upper and lower boundary are interconnected with the periodic conditions. The exit boundary (the right boundary) condition is an extrapolated outflow [7]. Following previous studies[8,9], the reactive Euler equations are used as governing equations for modeling the detonation flow field with a two-step induction-reaction kinetic model [10]. The dispersion controlled dissipation scheme [11] together with a 3rd order Runge-Kutta algorithm are used to approximate the solution of the governing equations. The chemical reaction parameters are obtained based on the simplified mechanism, considering a flight condition of 18km (p = 7565.2Pa, T = 216.7K) and the stoichiometric hydrogen-air mixture. Hence, the main parameters are set to be: $Q = 25.31$, $\gamma = 1.32$, $E_I = 6.52T_S$, $E_R = 1.00T_S$.

3 Results and discussion

3.1 Basic structure

The test cases with the ignition zone Z2, varying the inflow stagnation temperature T_t, are first simulated to illustrate the basic structure of RDW, as shown in Fig. 2. We can see that the RDW structure is composed of oblique detonation, oblique shock induced by detonation, the slip line evolving into the Kelvin-Helmholtz (K-H) instability, the contact surface between fresh mixtures and products, and so on, which almost agree with the previous studies [4]. Furthermore, it is observed that the temperature T_t can affect the flow structures of RDW, i.e., the number of RDW increases with increasing T_t. A small change of the inflow temperature has little effect on the mass flow for the given parameters. Hence, the dynamics of flow and heat release plays a noticeable role in detonation stability and initiation partly. Previous experimental study [12] has shown that an increase in the number of detonation waves within the combustor depends on the normalized perimeter (p/λ) of the detonation wave. As the value (p/λ) increases to the critical value, the number of detonation waves trigger a transition to more stable state of operation. For the single stable RDW in Fig. 2a and 2b, the detonation can propagate stably for a long time and the detonation wave height and intensity gradually tends to be stable. However, the increasing inflow temperature breaks the balance and makes the number of RDW increase to a new stable state.

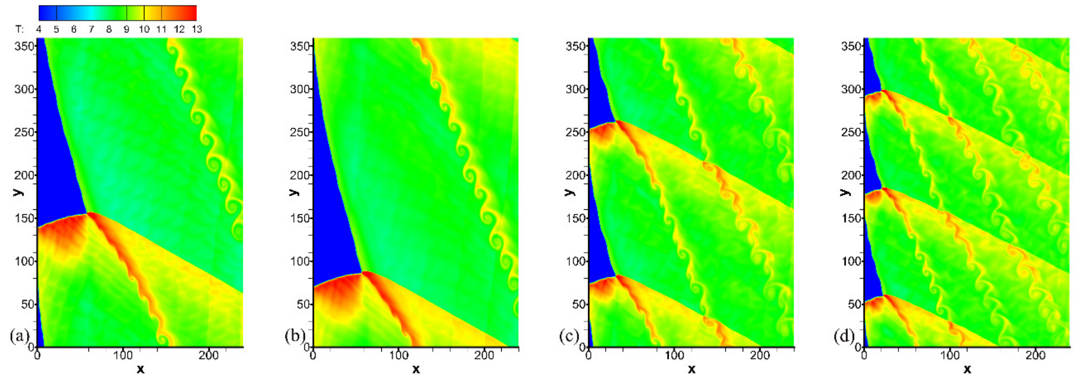

Figure 2. Temperature field of RDW with T_t = 3.8 (a), 3.9 (b), 4.0 (c), and 4.1 (d).

3.2 Effects of heat release rate

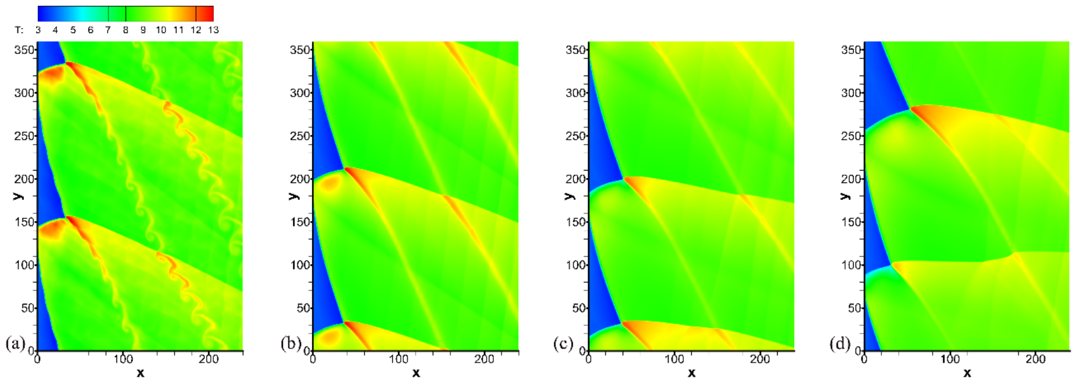

Figure 3. Temperature field of RDW with T_t = 4.1 and k_R = 2.0 (a), 1.0 (b), 0.5 (c), and 0.4 (d).

By varying the heat release rate controlled by the pre-exponential factor of the second reaction step, the effects of chemical kinetics on the RDW structure are also investigated. This rate k_R controls the detonation instability by changing the coupling between the leading shock and heat release front [10], and plays a vital role in the detonation initiation and propagation. The consequence of varying k_R while keeping other chemical parameters constant is the change of the induction-to-reaction length ratio, which is known to affect gaseous detonation instability [10]. Fig. 3 shows that the flow structures of RDW with varying k_R. Compared with the aforementioned results with k_R =3.74 (see Fig. 2d), the general wave configuration changes obviously. It can be observed that the number of RDW decreases from 3 to 2 when the rate is reducing from 3.74 to 2.0. Concurrently, the length of the detonation front increases a little in order to accommodate the new flow field structures. By decreasing the rate k_R from 2.0 to 0.4, although the number of the detonation front keep the same, the characteristics of the entire flow structures have some distinct changes, like temperature and pressure, and so on. It is worth noting that the triple points of the detonation wave front and the K-H instability of the contact surface gradually dies down with the decreasing k_R. These phenomena are in good agreement with the finding from previous works using the two-step induction-reaction model [8-10], regardless of the instability of one-dimensional detonation or two-dimensional oblique detonation. In other words, the detonation front will become more stable as the rate k_R decreases. However, it is interesting that the entire RDW flow flied gradually become unstable with varying k_R from 1.0 to 0.4 (see Fig. 3b-d). These results in Fig. 3 have run for a very long time, for the low value k_R, the detonation pressure and height experience high-amplitude oscillations through the operating cycle. These results present the presence of another instability mechanism that may influences the wavelet behavior, and this phenomenon deserves more attention.

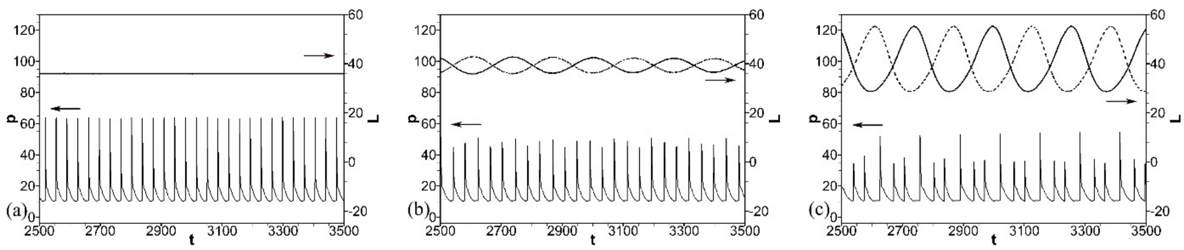

Figure 4. Evolution of the detonation front length and the pressure with T_{st} = 4.1 and k_R = 1.0 (a), 0.5 (b), and 0.4 (c).

To gain an understanding of the evolution of multiple detonations and the underlying mechanism, the long-time simulations are performed to eliminate the effects of initiation. The detonation height and the pressure of a fixed point in the flow are recorded as time goes on, which are plotted in Fig. 4. In contrast to the result with the high value k_R =3.74, although the number of RDW reduces to 2 with decreasing k_R to 1.0, the height and intensity of RDW still stayed the same value as time, which can be referred to being a stable state. By decreasing k_R to 0.5 (see Fig. 4b), an interesting phenomenon that the detonation height and pressure changes periodically in forms of an approximate sinusoidal wave, appears in the current computation time. However, the amplitude of oscillation decreases gradually. In other words, the height of this two RDWs will achieve a constant value with a very long time, which is regarded as a stable state. When the rate k_R reduces to 0.4, it can be observed that the oscillation amplitude of the detonation height remains the same and there is no the trend of the decay. The pressure and height of the detonation front oscillates with strong regularity and persistence. As mentioned previously, increasing the rate k_R improves the instability of the detonation front to a certain extent, which results to the formation of the triples points or cellular structures on the wave front. For the rotating detonation waves in the same geometric condition, the higher k_R value increases the instability of detonation front and there may be more detonations in chamber. Hence, decreasing k_R reduces the number of detonation waves and increases the detonation height. Besides, the entire RDW flow structures become unstable and the height and pressure of detonation oscillates periodically to maintain the operation of the whole flow flied. It can be predicted that the continuous reducing of the rate k_R will result in the only one detonation wave in chamber for the given inflow and geometry condition, and even fails to maintain the existence of detonation waves for a long time.

3.3 Possibility of multi-pattern induced by initiation

The RDW flow fields are composed of complex wave configurations and varied chemical reaction processes. The patterns of the RDWs after ignition may be affected by the initial condition. To intuitively present the possibility of multi-pattern waves in a rotating detonation combustor, three ignition zones are chosen to solve the RDW structures with varying T_t. Fig. 5 shows the RDW results, using three ignition zones respectively, with the same temperature T_t =4.1. These results reveal an interesting physical phenomenon about the formation of multiple detonation. Compared to the ignition zone Z1 of Fig. 5a, the initiation zone Z2 has only a wider scale along the x- direction. However, the final stable flow field has a big difference between them, where the former contains one single-wave and the latter is triple-waves. The greater initiation energy will be propitious to the formation of detonation wave and supports much waves in the confined space. In contrast to the ignition Z2, it is worth noting that even though the zone Z3 has greater ignition area, there are two waves in chamber. These results may be a little different from those mentioned earlier, while it can be explained by the following reasons. Compared to the zone Z2, the rarefaction waves at the end of CJ detonation (from 0 to 100 along y- direction of the zone Z2) reduces the concentrated release of energy and represses the formation of the multiple detonation waves, and finally results in the double-waves in contrast to the zone Z2. Besides, the generalizing dependences of the RDW flow structures on T_t and the initiation pattern are shown in Fig. 6. In general, these results present such a fact that the greater stagnation temperature T_t promotes the formation of wave structures and the RDW flow field has various forms of self-sustaining propagation, even though given the same inflow condition, chemical parameters and geometric condition.

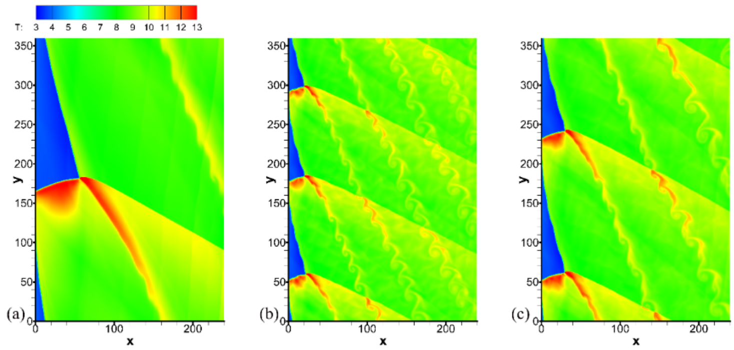

Figure 5. Temperature flied with T_t =4.1 and different initiation pattern: Z1 (a), Z2 (b) and Z3 (c).

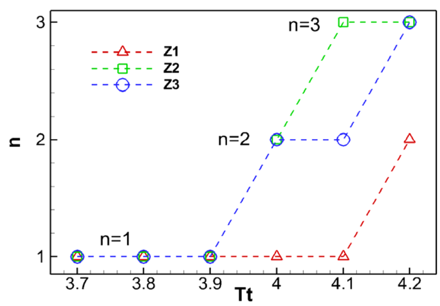

Figure 6. The generalizing dependences of the number of detonation waves on T_t and the initiation pattern.

4 Conclusions

Two-dimensional rotating detonation waves were simulated to investigate the wavelet pattern varying the inflow stagnation temperature, the initiation pattern and the heat release rate. Using the two-step induction-reaction model, we perform the generalizing dependences of rotating detonation wave number on some thermodynamic parameters and analyze the instability of multiple rotating wave.

By increasing the stagnation temperature T_t, it is found that there exists various forms of flow flied, like single wave, double waves and treble waves. Besides, the flow structures are quasi-steady and the detonation wave height and intensity can keep one constant over time. However, an interesting distinct detonation phenomenon appears, which indicates the importance of coupling of flow and hear release on the instability of rotating detonation flow flied. Decreasing k_R, the triple points of detonation surface weaken and disappear gradually, but the entire rotating detonation waves become more unstable than high k_R. To investigate the possibility of multi-pattern induced by initiation, three different ignition zone are chosen at different stagnation temperature. The present results show that, generally speaking, the greater ignition energy is more conductive to formatting multiple rotating detonation waves. The basic understanding of the rotating detonation is not only helpful to know the physical mechanism, but also for engineering application. Further fundamental research on the rotating detonation are necessary in the future.

Acknowledgement

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