One Inducing Factor of the Operational Mode Transition in A Rotating Detonation Engine

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1 Introduction

In recent years, engines using detonation for energy release such as the pulse detonation engine (PDE), oblique detonation wave engine (ODWE), and rotating detonation engine (RDE) have attracted much attention due to their expected application prospect. Among them, RDE is currently considered as one of the most promising aerospace power devices since it has simple structure and only requires one ignition to provide sustained thrust in compact combustor. To bring the concept of RDE into practical use, significant researches have been performed. In 1960s, Voitsekhovskii [1] achieved short-lived rotating detonation. Up to now, many characteris of RDE have been widely studied, such as the Engine ignition characteris [2], the structure of flow field in RDE [3], the stability of detonation wave (DW) in combustor [4], the operational mode of RDE [5, 9]. Most early studies on RDE only focus on the presence of one DW in the annular detonation combustor. Recent studies have shown that in some cases the engine can maintain multiple DWs [5–8].

As a power device, it is important for RDE to work at a stable and desired operational mode (defined by the number and the propagating direction of DWs in the combustor). However, the operational mode is not always fixed. The number of DWs may instantaneously change during the operational process when operational conditions or injection conditions vary [5–7, 10]. Thus, We conduct the study on the engine from ignition to stable operation with different number of initial DWs to investigate the multiplicity phenomenon in rotating detonation flow field. The detailed chemical reaction model is adopted to calculate the reaction rate of the pre-mixed hydrogen, oxygen, and nitrogen mixture. Then, the evolution processes of rotating detonation flow field are analyzed. In the second part of this study, we provide a relationship between the number of DWs and the mode of evolution quantitatively.

2 Physical model and numerical method

Unsteady Euler equations coupled with detailed chemical reactions are used in this study.The governing equations are solved by using the operator-splitting technique and is based on the PISO/SIMPLE algorithm. The Kurganov-Noelle-Petrova (KNP) scheme is used for convective fluxes.

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The schematic diagram of the RDE combustor and computational domain are shown in Fig. 1. The annular combustor of the RDE has a length of 100 mm. The mixture is injected into the combustor from the bottom inlet.

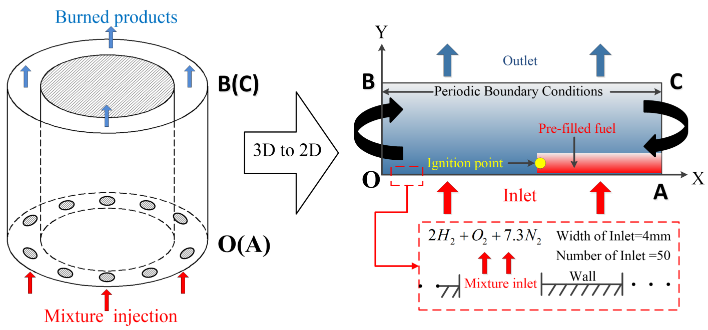

Figure 1: Schematic diagram of combustion chamber,computational domain, and injector

3 Results and analysis

For a given engine, one-wave operational mode could be quite stable. As the filling height of fuel or mixture reactivity is increased, the engine is prone to producing a higher order of waves [7]. The boundaries demarcating different operational modes are determined by the engine design parameters. In order to predicted and control the operational mode of RDE, the factors inducing operational mode transition need to be studied. To achieve this goal, the engine is initiated with different operational modes (different number of initial DWs).The following evolution processes are observed and analyzed.The acceleration of chemical reactions on the fuel-detonation product contact face is found to be the key factor inducing an operational mode transition in these simulations. Based on this discovery, the mode transition is related to the characteristic time of contract face and the recirculated product interactions quantitatively.

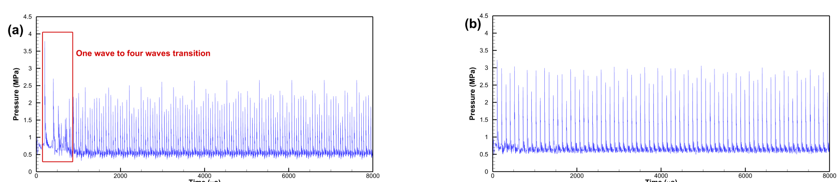

Figure 2: Pressure traces of case (a) and case (b) from 0 μs to 8000 μs at the point x=160 mm, y=10 mm

The final operational modes of the engine under different number of initial DWs (defined as N_{initial}) are shown in Table 1. Under the traditional single-ignition condition in case (a), the single-wave operational mode cannot maintain. New DW fronts are spontaneously formed during the evolution process(see Fig. 2a) . The engine finally operates in four-wave mode. When the number of initial DWs increases to 2 in case (b), the two DWs propagate stably from beginning to the end of simulation(see Fig. 2b). Only some waxing and wanning instability [4] is observed. When the number of initial DWs is 3 in case (c), evolution process is similar with that of case (b).

In order to furtherly understand the mechanism behind this phenomenon and to predict this transient change in flow field, the details of evolution process need to be discussed. Figure 3 shows the pressure contours

Table 1: Simulation results under different number of initial DWs

Case	N_{initial}	Operational Mode	u_{DW}(m/s)
Case (a)	1	Four-wave mode	1403
Case (b)	2	Two-wave mode	143.7
Case (c)	3	Four-wave mode	1421.5

during the evolution process of case (a). Due to the existence of reasonably pre-filled fuel, the DW is established rapidly in the combustion chamber. Then, the single DW dominates the flow field until 476 µs. From 512 µs to 780 µs, it is unstable stage, in which DWs are spontaneously formed and interacted with each other. At 512 µs, the chemical reaction rates at point A, B suddenly increase and cause pressure to rise simultaneously. Two compression waves can be clearly seen. The two compression waves subsequently develop into DWs respectively.

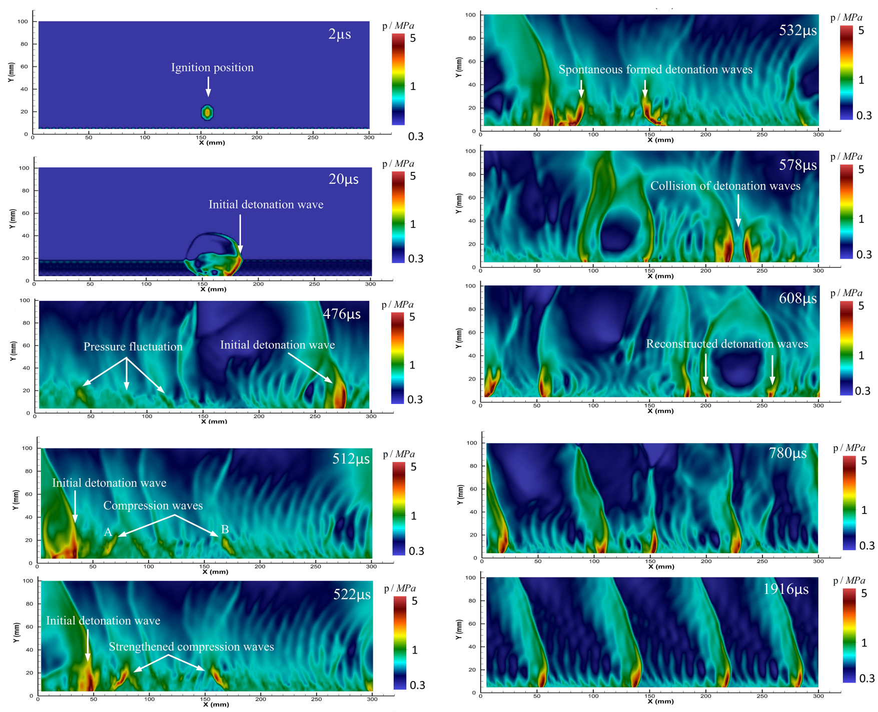

Figure 3: Pressure contours of case (a)

During the short period from 512µs to 532µs in which new DWs are formed, four important features of the flow field are observed, which can help us figure out the underlying mechanism of this phenomenon.(I) Fuel injection and nonuniform fuel distribution cause pressure fluctuation in the x direction near the inlet. These weak waves are labeled with arrows in Fig. 3 and could be seen throughout the whole evolution process. (II) Determined by the nozzle installation position, the fresh mixture is directly injected into the detonation products. As a result, the distribution of reactive mixture is funneled. (III) On the contact face between fresh mixture and high temperature detonation products, chemical reactions take place . Moreover, chemical reaction intermediates (such as OH) tends to concentrate in the area between two fuel injection areas. (IV)Newly-formed DWs originate inside the reactive mixture, and two strong compression waves are closely combined with its corresponding chemical reactions. Feature I to III indicate the flow field is suitable for the acceleration of chemical reaction. More importantly, the above four features are consistent with the characteris of deflagration-to-detonation transitions (DDT) in flow field summarized by Oran et al. [11]. Therefore, we speculate that the spontaneous formation of new DWs is the result of DDT caused by the contact face chemical reaction.

As chemical reaction occurring on the contact face changes the fuel accumulation in front of DWs. The height of fuel layer (H_2) initially increases due to the fuel injection and then decreases due to the excessive consumption results from the contact face chemical reaction. There are two key time nodes for the change of fuel thickness: t_{W} and t_{L}. When the fresh mixture is completely consumed somewhere near the inlet, it takes time t_{W} to accumulate to a thickness greater than or equal to h_{cr}. More importantly, the fuel is consumed through time t_{L} to a thickness less than h_{cr}. If the time when DW reaches the specific located between t_{W} and t_{L}, the excessive acceleration of chemical reaction on the contact face will be avoided, and DWs will experience 'quasi-steady evolution'. Otherwise, 'unstable evolution' will occur. Thus, the premise condition for “quasi-steady evolution” of DWs can be expressed as:

$$t_{\mathrm{W}} \leq t_{\mathrm{T}} \leq t_{\mathrm{L}} \tag{1}$$

For simplicity, the DWs are supposed to be evenly spaced in the combustion chamber. Then, the premise condition for “quasi-steady evolution” can be expressed as:

$$t_{\mathrm{W}} \leq \frac{L}{u_{\mathrm{DW}} N_{\mathrm{DW}}} \leq t_{\mathrm{L}} \tag{2}$$

$u_{\mathrm{DW}}$is the average DW velocity. L is the average perimeter of the annular combustion chamber. N_{DW} is the number of DWs in the combustion chamber. The stable propagation of DW depends on the relationship between $L, u_{\mathrm{DW}}, N_{\mathrm{DW}}, t_{\mathrm{W}}$ and t_{L}. Here, we focus on the relationship between the number of DWs (N_{DW}) and the stability of the flow field, so two dimensionless parameter N_{L} and N_W are defined as:

$$N_{\mathrm{W}} = \frac{L}{u_{\mathrm{DW}} t_{\mathrm{W}}} \tag{3}$$

$$N_{\mathrm{L}} = \frac{L}{u_{\mathrm{DW}} t_{\mathrm{L}}} \tag{4}$$

Then it can be deduced: the premise condition for “quasi-steady evolution” requires the number of DWs to meet the following condition:

$$N_{\mathrm{L}} \leq N_{\mathrm{DW}} \leq N_{\mathrm{W}} \tag{5}$$

If the relationship prescribed in formula (5) is satisfied, DWs can propagate stably and the number of DWs will be fixed. Otherwise, the number of DWs is going to change until relationship (5) is satisfied. Thus, by comparing the number of DWs and N_{L}, the subsequent evolution process can be predicted.

4 Conclusion

The relationship between the number of DWs and the stability of the rotating detonation flow field is clarified by numerical simulation with detailed chemistry reaction model. The simulations revealed that chemical reaction occurring on the contact face speeds up over time. The acceleration of chemical reaction rates consumes the fuel prepared for the coming DW. Furthermore, it has the potential to trigger deflagration-to-detonation transitions and induces new DWs. When new DW is formed, the flow field shows great instability. As the contact face chemical reaction is restrained with the increase of the number of DWs, the RDE operates more stably when the number of DWs is greater than a certain value. This phenomenon is observed but unexplained in previous studies of RDE experiments. In order to predict such unstable operational mode change before it occurs, the parameter so called "N_L" is proposed. If the number of DWs in the combustor is less than N_L, the unstable operational mode change is inevitable. Also, the value of N_L for a given engine represents the minimum number of DWs the engine can sustain stably.

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