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Theoretical analysis of interaction between rotating detonation wave and upstream flow field

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Abstract

In order to investigate the interaction between the detonation wave and the upstream airflow, a non-premixed air-breathing rotating detonation combustor with an axial inlet was simulated by using the Navier-Stokes equation of two-dimensional unsteady reaction, a complete structure of rotating detonation wave and upstream flow field was obtained, and the interaction between the detonation wave and the upstream airflow was analyzed by a combination of equation derivation and numerical simulation. The equations for calculating the airflow velocity after the forward shock wave and the height of detonation wave were derived and verified. The results show that the rotating detonation wave would trigger the forward shock wave propagating in the upstream, and the velocity would be weakened and the direction would be deflected of the airflow passing through the forward shock wave. If the airflow velocity drops to a negative value after passing the forward shock wave, there will be no air injection into the combustor. The velocity of the airflow after the forward shock wave is inversely proportional to the velocity of the detonation wave, the temperature of the incoming airflow and the pressure ratio at the forward shock wave. The angle of the forward shock wave is inversely proportional to the velocity of the detonation wave. The interaction between detonation wave and incoming flow is summarized, the higher the intensity of the detonation wave, the slower the recovery time of the airflow after the forward shock wave, and the lower the height of the detonation wave.

Keywords: *air-breathing rotating detonation engine; forward shock wave; incoming flow; detonation wave height; theoretical derivation*.

1. Introduction

Rotating detonation engines (RDEs) have attracted more attention in past few years due to their advantages, such as high heat release intensity, simple structures and high theoretical thermodynamic cycle efficiency [1-3]. RDEs include rotating detonation rocket engines and air-breathing rotating detonation engines (ARDE) [4,5]. In the ARDE, a forward shock wave will be induced in the isolator due to the high-intensity rotational propagation of detonation wave. The incoming flow will be affected and the isolator will be choked in severe cases, which will affect the stable propagation of the rotating detonation wave (RDW) [6]. Therefore, it is of great significance to analyze the variation characteristics of the forward shock wave induced by the RDW, and study the interaction between the RDW and the incoming flow for the stable operation of the ARDE.

2. Numerical method and calculation model

The case in this study was solved using the RYrhoCentralFoam solver based on OpenFOAM. This solver employs the Navier-Stokes equations using the compressible method. In recent years, the RYrhoCentralFoam solver has been successfully applied to the simulation of RDE in gas and liquid phases [7-9]. In this study, a simplified 6-species-2-step mechanism for kerosene/air was used for the chemical reaction.

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The physical model used for numerical simulation in this study is shown in Fig. 1. The computational domain is a two-dimensional rectangular domain. The boundary conditions are also marked in Fig. 1.

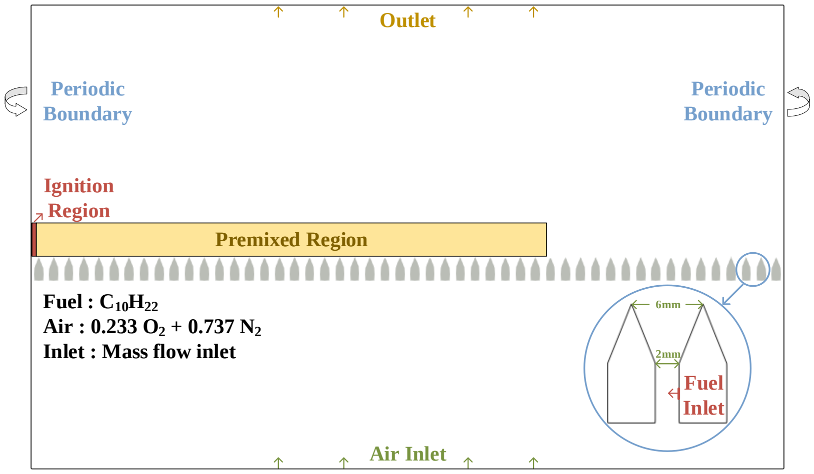

Fig 1. Schematic of the computational domain and boundary conditions

3. Results and discussion

Figure 2 shows a stable non-premixed rotating detonation flow field, there are typical structures such as detonation wave, oblique shock wave and reactant fill region and so on. Due to the non-premixed reactant flow, there are more gas pockets and unburned regions after the detonation. The ripple shape of the detonation wave front is produced by the interference of the injection geometry. The detonation wave causes a forward shock wave to propagate upstream and reflect in the air plenum chamber. In the path of the forward shock wave, the air flow is slowed down, and the reactants cannot be injected in a region after the detonation wave. According to the shape of $C_{10}H_{22}$, it can be seen that the direction of the air flow has been changed. The forward shock wave influences both the velocity and direction of air flow, and influences the injection and mixing of reactants in the combustor.

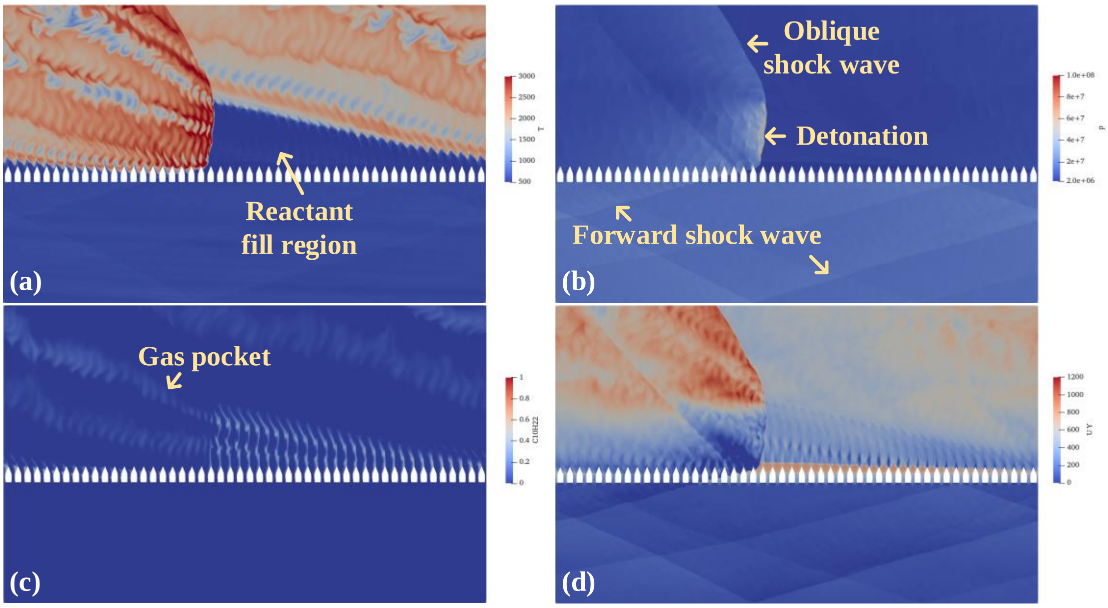

Fig 2. Instantaneous (a)temperature; (b)pressure; (c)C10H22 distribution; (d)velocity on the Y axis

In this section, the change of flow velocity will be analyzed theoretically when it passed the forward shock wave. Figure 3 shows the simplified diagrammatic sketch of rotating detonation wave, where v_1 is the flow velocity that is in front of the forward shock wave, and v_2 is the flow velocity that has passed the forward shock wave. Where v_s is the propagation speed of the forward shock wave, that is the propagation speed of the rotating detonation wave, which is considered to be the CJ velocity in the theoretical analysis. Shock-wave angle β is the intersection angle between the forward shock wave and the horizontal direction, and θ is the transition angle of v_2 with respect to v_1. v_2 and θ can be used to quantitatively describe the change of flow velocity after it passed the forward shock wave.

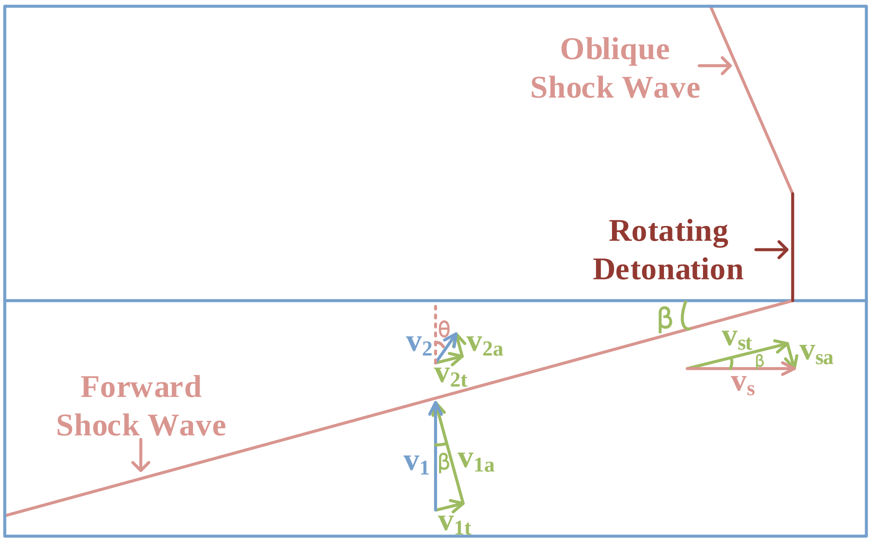

Fig 3. Diagrammatic sketch of rotating detonation wave

The airflow velocity v_2 after the forward shock wave and its transition angle θ of the two-dimensional rotating detonation combustor can be solved:

$$v_2 = \sqrt{\frac{v_1^2[2kRT_1 + (k-1)v_{1a}'^2]^2 + \left\{v_s[2kRT_1 + (k-1)v_{1a}'^2] + [(k+1)v_{1a}']\left(v_1\sqrt{v_1^2 + v_s^2 - v_{1a}'^2} - v_{1a}'v_s\right)\right\}^2}{[(k+1)v_{1a}']^2(v_1^2 + v_s^2)}} \quad (1)$$

$$\theta = 90° - \sin^{-1}\left(\frac{v_1\sqrt{v_1^2 + v_s^2 - v_{1a}'^2} - v_{1a}'v_s}{v_1^2 + v_s^2}\right) - \tan^{-1}\left(\frac{[2kRT_1 + (k-1)v_{1a}'^2](v_1^2 + v_s^2)}{v_1^2\sqrt{v_1^2 + v_s^2 - v_{1a}'^2} - v_{1a}'v_1v_s} + \frac{(k+1)v_{1a}'v_s}{v_1}\right) \quad (2)$$

The comparison result is shown in Fig. 4. As a result, the accuracy of equations can be verified.

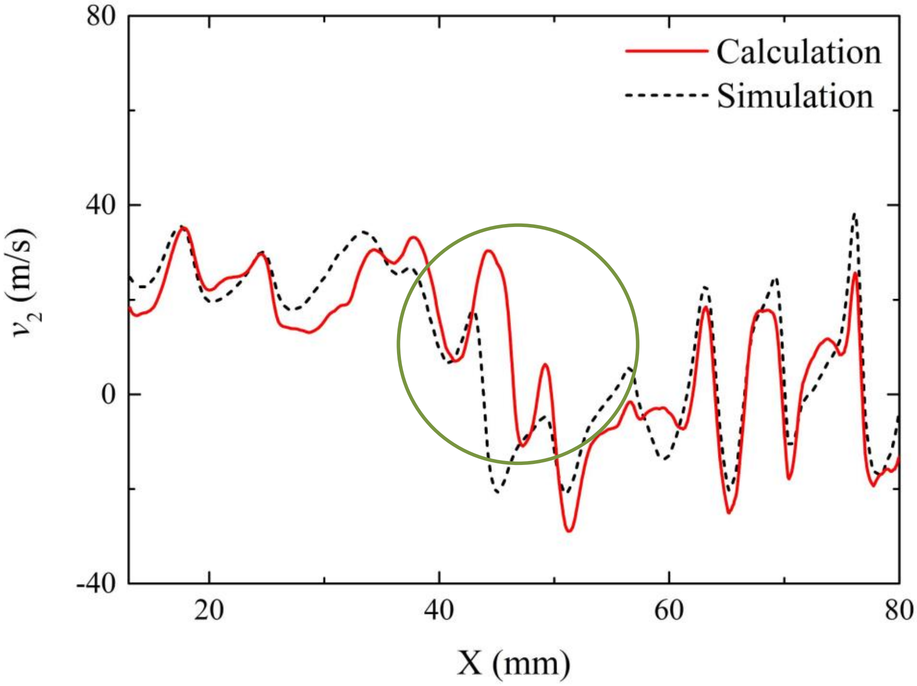

Fig 4. Comparison of the results of calculation and numerical simulation

There are shock waves in the nozzle expansion section, and the states of velocity and shock wave in the nozzle are shown on the left in Fig. 5. The airflow is sonic at the throat of the nozzle, accelerates to supersonic in the expansion section, and decelerated to subsonic propagation after the shock wave.

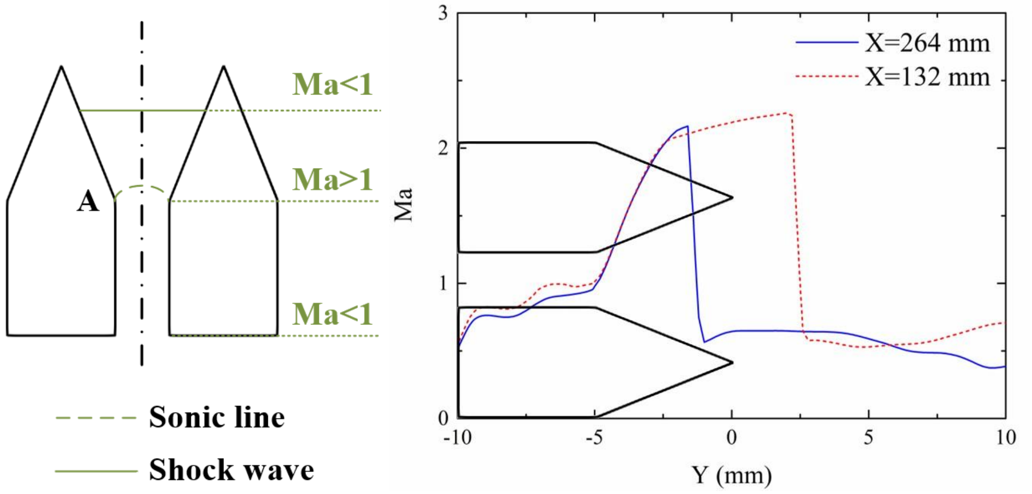

Fig 5. Diagram of velocity and shock wave state (left); Mach curve (right)

The height of detonation wave can be derived from the above equations:

$$H=\int_{0}^{t}\frac{\sqrt{9kRT^{*}\left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}}\left(\frac{p_b}{p^{*}}\right)^{2}+2kRT^{*}(k-1)}-\left(\frac{k+1}{2}\right)^{\frac{k+1}{2(k-1)}}\left(\frac{3p_b}{p^{*}}\right)\sqrt{kRT^{*}}}{k-1}dt \tag{3}$$

The highest position reached by the airflow in the previous period can be obtained, that is, the height of the detonation wave. It is represented as shaded in Fig. 6, and the detonation wave height can be obtained as H is 0.0359m. Compared with the numerical simulation result, as shown in Fig.15, the position of the line segment ranges from Y is 0m to Y is 0.0359m. The detonation wave height calculated by the equation is basically consistent with the detonation wave height obtained by the numerical simulation result, and the theoretical derivation is considered accurate.

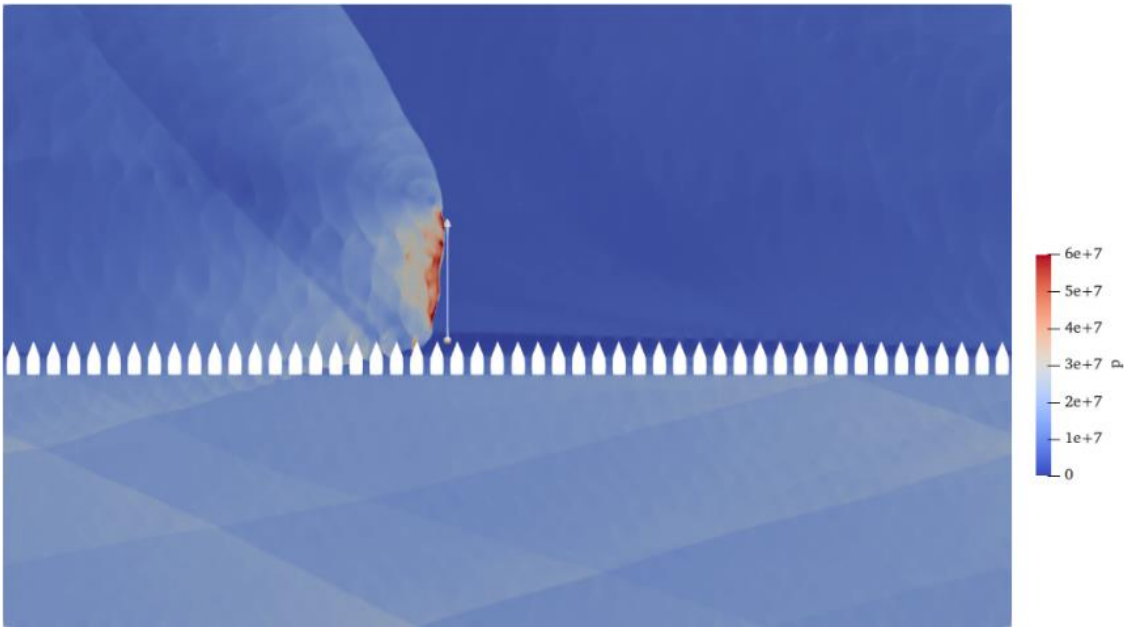

Fig 6. Comparison of the results of calculation and numerical simulation

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