Effects of mixing level and temperature of injection in rotating detonative combustion

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1 Introduction

The detonation is an extreme combustion phenomenon, which propagates at supersonic speed. Detonation wave combustion has the characteristics of fast heat release and high thermal efficiency [1]. It is an ideal combustion mode for high Mach number engines. The detonation propulsion system has the characteristics of short combustion chamber length, light engine weight and high efficiency. At present, the widely studied detonation engines are pulse detonation engine (PDE), oblique detonation engine (ODE) [2-4] and rotating detonation engine (RDE) [5,6]. For RDE, the detonation wave propagates circumferential direction in the combustor, which has high thermal efficiency and wide flight range.

The concept of RDE is proposed in 1960s [7]. After that, Bykovskii [8,9] achieved the rotating detonation combustion experimentally with hydrogen, methane and dimethyl-methane blend fuel. They found out that the rotating detonation wave (RDW) in the combustor has different working modes such like the symmetric dual-wave and asymmetric dual-wave mode. Frolov [10] carried out the experiment in large annular combustor. The single-wave mode and multi-wave mode of RDW was observed. The multiple effects of size of combustor, stagnation pressure of injection and mass flow has been reported in the following study [11]. The rocket mode RDE is verified, and the basic structure is observed by simulation [12-16].

However, the mixing process in rocket mode RDE is complicated especially when fuel and oxidant inject with different temperature. In this study, the hydrogen-air RDW is simulated with different injection temperature and mixing level. Further the binary effects of temperature and mixing level are discussed.

2 Models and Methods

2.1 Numerical methods

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RDE combustion chamber's cylindrical surface is expanded to a rectangle, ignoring the axial scale. For the two-dimensional simulations, the ideal flow model is given by the reactive Navier-Stokes equations. The dynamic viscosity is modeled by Sutherland's law. The chemical kinetic model used in this study is taken from a comprehensive H2/O2 kinetic model for high pressure combustion, including 27 reversible chemical reactions and 13 components (H2, O2, H2O, H, O, OH, HO2, H2O2, N2, Ar, He, CO, CO2). The implicit Euler scheme is used for temporal discretization. The second-order semi-discrete and non-staggered Kurganov–Noelle–Petrova scheme with van Leer's splitting is used to solve the governing equations. A sufficient number of sub-reaction steps are involved to ensure the overall accuracy to overcome the stiff problem.

2.2 Physical model

The two-dimensional rectangular domain as shown in Fig.1. The domain size is fixed at 280mm× 100mm.The cell spacing is 0.2mm fill in the domain. The top and bottom boundaries(x -direction,100mm) are modeled by periodic boundary conditions. The non-premixed gas(H2/Air) is axially injected into the combustion chamber through the nozzle at the left boundary separately, and the right boundary is interpolated under the assumption of zero gradient for all flow parameters. The area ratio of oxidant and fuel inlets is fixed at 2:1. The flow rates of fuel and oxidizer are determined from the isentropic expansion relations between the stagnation pressure and local pressure near the inlet. The stagnation pressure of injection P_0 is set to be 1.0MPa and the stagnation temperature T_0 is variable. A rectangular zone (the red zone in Fig.1) with high temperature and high pressure is set to produce a detonation wave.

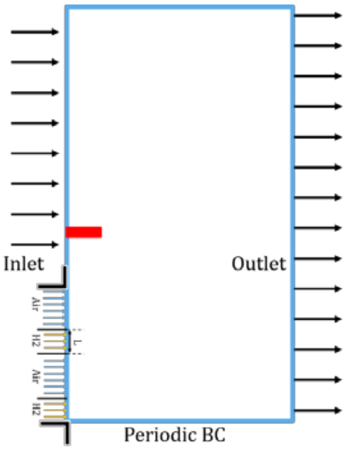

Figure 1: Schematic diagram of computation model.

At the initial moment, it is considered that the premixed stoichiometric H2/Air gas (with initial temperature of 300K and pressure of 1atm) distributed in the chamber, and the initiation area is set near the left boundary.

3 Results and discussion

3.1 The effect of temperature of injection

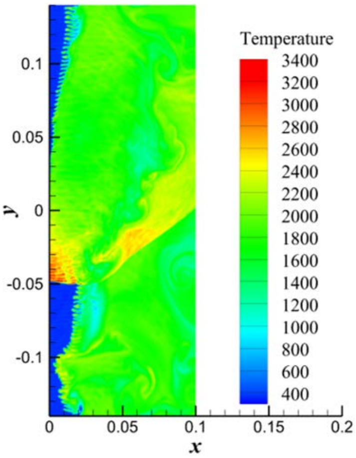

Figure 2: The temperature contour for the case with for A_{H2} = 1mm, T_0 = 350K.

The fuel H2 and oxidant air is injected separately into combustor of RDE. Fig.2 shows that the temperature contour of stable mode of RDW with A_{H2} = 1mm, T_0 = 350K. It can be observed that there is only one detonation wave in the combustor. The temperature of combustible gas behind the leading shock wave of detonation wave was sufficient to trigger the reaction. In this study, this case is selected as the basic case.

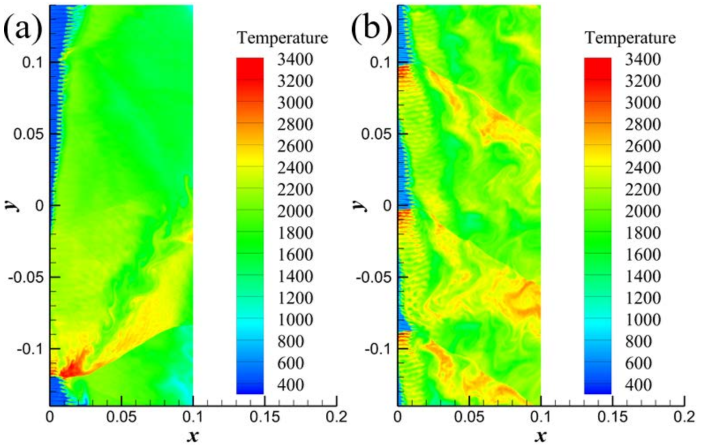

Figure 3: The temperature contours for the case with A_{H2} = 1mm, (a) T_0 = 450K, (b) T_0 = 600K.

For study the effect of stagnation temperature T_0 in RDW, the cases with T_0 = 400K, 450K, 500K, 550K and 600K have been simulated. Fig. 3 shows that the temperature contours of RDW field with T_0 = 450K and T_0 = 600K. In Fig.3(a), single detonation wave mode of RDW can be observed, and the structure of RDW is similar to the case of T_0 = 350K shown in Fig.2. The same wave mode and structure are also observed in the cases of T_0 = 400K, 450K, 500K, 550K. When T_0 increase to 600K, it can be observed that there are three detonation waves propagating in the combustor, and all the detonation waves has a same propagate direction, as shown in Fig. 3(b). It can be concluded that increasing stagnation temperature may lead more detonation wave in the combustor and more complicated field structure.

3.2 The effect of mixing level

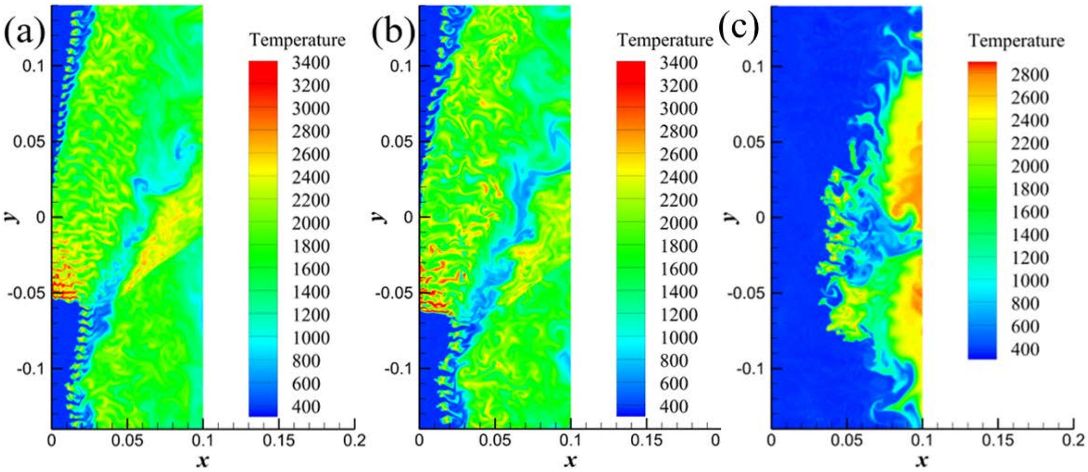

Figure 4: The temperature contours for the case with T_0 = 350K, (a) A_{H2} = 2mm, (b) A_{H2} = 3mm, (c) A_{H2} = 4mm.

In this section, the effect of mixing level in RDW is studied. The mixing level of Hydrogen and air is controlled by the parameter A_{H2}. The total area of inlet nozzle and the rate of area nozzle of hydrogen and air remain constant. Obviously, increasing A_{H2} leads to the lower level of mixing. Fig. 4 shows that the result of the cases with T_0 = 350K and A_{H2} = 2mm, 3mm and 4mm. The single wave mode is observed in the cases of T_0 = 350K and A_{H2} = 2mm, 3mm, but the detonation wave surface seems to more unstable. The low temperature zones along the slip line of RDWs can be seen in the cases of low mixing level and the area increases when the mixing level decreases. When the mixing level decreases further, there is no detonation wave and the combustion waves flow out of the combustor as shown in Fig. 4. It indicates that low mixing level of injection will lead to the disappearance of the RDWs.

3.3 The binary effects of mixing level and temperature

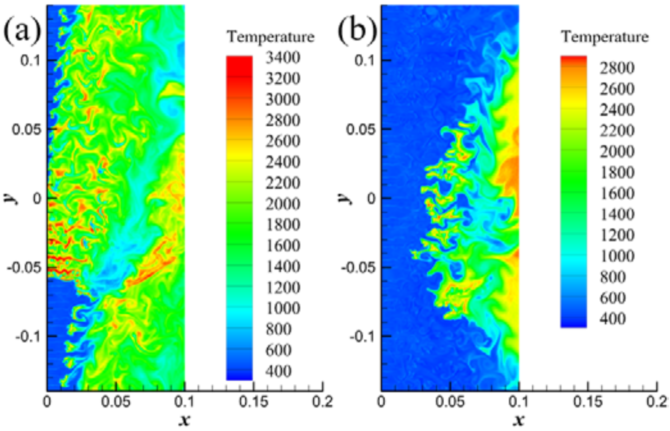

Figure. 5: The temperature contour of the case with T_0 = 450K, (a) A_{H2} = 4mm, (b) A_{H2} = 5mm.

In the last section, the case with A_{H2} = 4mm, T_0=350K, the detonation wave cannot be initiated. When increasing T_0 = 450K, the single detonation wave mode is observed, as shown in Fig. 5(a). It indicates that with higher stagnation temperature of injection, the RDW can propagate in the lower mixing level. The area of low temperature zone is smaller. The same phenomenon can be observed when mixing level decrease further in T_0 = 450K. The detonation wave disappears in the case of A_{H2} = 5mm, as shown in Fig. 5(b). In generally, it can be concluded that the formation and propagation of RDW is controlled by both stagnation temperature and mixing of fuel and oxidant. The RDWs of low mixing levels can propagate in the higher stagnation temperature.

4 Conclusion

In this study, the effect of stagnation temperature and mixing level of hydrogen and air in the propagation of RDW in combustor are investigated, through solving the Navier-Stokes equation with detail reaction. From the simulation results, it can be concluded that the formation and propagation of RDWs are effected by both stagnation temperature of injection and mixing of fuel and oxidant. Higher stagnation temperature make RDW propagation mode transfer from single wave mode to the multiple wave mode and lower mixing level leads to the disappearance of detonation wave. The coupled effects of stagnation temperature and mixing level are investigated. With the higher stagnation temperature, the RDWs can be reestablished, but the RDWs still disappear if the mixing is too bad. Deeper investigations about connections of this two factors need to be done.

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