Active Direction Control in Rotating Detonation Combustor

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1 Introduction

In development of rotating detonation engines, serval operation modes of rotating detonation waves have been reported and the transition mechanism between these modes have been investigated either [1]-[2]. But the propagating direction of rotating detonation waves is still uncertain in both experimental tests and numerical simulations. For the initiation process in rotating detonation engines, two waves in opposite direction are produced and collide with each other. After initiation a transition process take place in the engine, where many collisions happen and the detonation waves form and extinct. Direction of detonation wave often changes in such complicated mode transition process until the flow filed tends to stable. This chaotic wave evolution process makes it difficult to determine the propagation direction of detonation waves.

Directing the detonation wave is necessary for the integration of rotating detonation engine and turbine when apply rotating detonation engine to aero-engine. The determination of detonation direction is of great significance to turbine blade design and optimization [3]. And appropriate direction of detonation waves can produce better performance, reporting by Bach et al. [4].

Sevral investigations have been conducted in order to contorl the direction of rotating detonation waves. Knowlen and Kurosaka [5] generate circumferentially moving shock waves by sequential firing of multiple spark plugs at a particular frequency. Kawalec [6] design a eccentric chamber to generate detonation wave propagrting in pre-determined direction. In both methods, asymmetric initiation conditions are constructed to control the direction of detonation wave. In this research, a directional control method for rotating detonation engine with pre-detonator is proposed, which can regulate the direction of rotating detonation wave during engine operating.

2 Numerical Method and Physical Model

Detonation wave is a supersonic combustion wave, is couple of the leading shock wave and the chemical reaction behind the wave. And the time scale of chemical reaction is many orders of magnitude smaller than that of fluid flow, so the influence of viscosity, thermal diffusion and heat conduction can be ignored [7]. An in-house program BYRFoam based on the open-source computational fluid dynamics (CFD) platform OpenFOAM® have been developed to solve flow and combustion on three-dimensional

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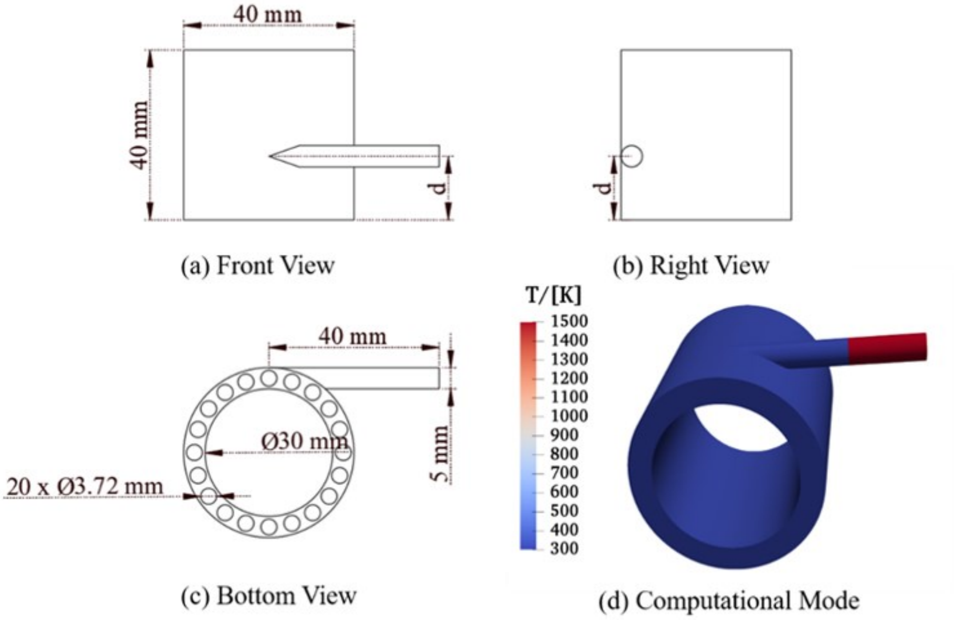
unstructured grids. A series of spatial discrete formats are adapted on the program, including HLL format, HLLC format, AUSM format, etc. And the semi-explicit and semi-implicit discretization method is adopted for time discretization. Time step is restricted by Courant number. In this research, unsteady three dimensional Euler equations coupled with chemical source terms are numerically solved using the HLL scheme in finite volume method. And explicit Euler time discretization is used in this case, while the time step is in the order of 10^{-9} s in actual simulation. The chemical reaction model used in simulations is a 9-species, 19-step hydrogen/air chemical reaction mechanism proposed by Hayashi [8]. Unstructured hexahedral grids with coarse grids of 0.2 mm and fine grids of 0.1 mm are used on the complex computational domain.



(a) Front View (b) Right View

(c) Bottom View (d) Computational Mode

Figure 1: Schematic of combustion Chamber

Figure 1 shows the schematic diagram of coaxial ring cavity with array orifice intake. Wherein, the inner diameter of the combustion chamber is r_{in}= 15 mm, the outer diameter r_{out} = 20 mm, and the axial length is Lz= 40 mm. Hydrogen/air premixed gas with equivalent ratio is injected through 20 circular holes uniformly distributed at the head of the combustion chamber. The radius of the holes is about 1.86 mm, and the air injection area ratio is about 39.63%. A pre-detonation tube, with length L_{pre}=40 mm and diameter d_{pre}= 5 mm, is tangent to the wall of the combustion chamber. The distance between the axis of the pre-detonation tube and the headwall of the combustion chamber is d= 5 mm.

Convergent nozzle inlet boundary conditions [9] is set on injection orifice. Hydrogen/air premixed gas is injecting with the total pressure p_{inlet}= 0.5 MPa, the total temperature T_{inlet}= 360 K. The exit of the combustion chamber is set as no reflected boundary conditions he other wall surfaces are set as mirror reflection boundary conditions. The combustion chamber and pre-detonator are initially filled with fresh gas with total pressure p_0 = 0.1 MPa and total temperature T_0 = 300 K. A hot spot is set at the far end of the pre-detonator for igniting as shown in figure 1d). The temperature of the hotspot is T_{high} = 1500 K and the pressure is p_{high} = 1 MPa.

3 Result and Discussion

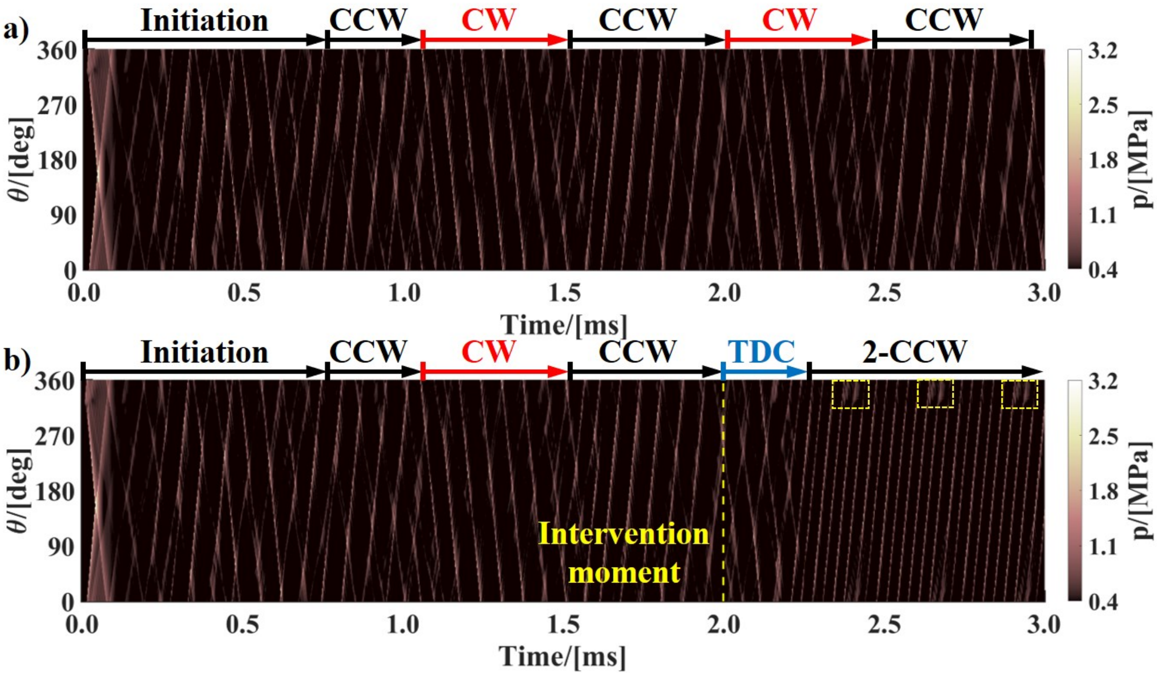


Figure 2: Trajectory of rotating detonation waves at cross-section 5mm downstream from headwall in combustion chamber a) without direction control method and b) with interference of direction control at 2.0 ms. CCW: Counterclockwise, CW: Clockwise, TDC: Transition induced by Direction Control.

Time-varying pressure distribution diagrams are illustrated to demonstrate the propagating mode of rotating detonation wave and the mode transition phenomenon in annular chamber. These diagrams are radial averaged pressure at the cross-section 5 mm downstream from headwall, rendering in azimuthal-time space. The definitoin of angle position θ is shown in figure 3 a), and the pressure data in figure 2 are only extracted from the cross-section of annular chamber encircled by white dotted circle in figure 3 a).

In this research, the distance of injection headwall and pre-detonator is d= 5 mm, and the pre-detonator exit is within the range of the detonation front. Complex reflection and diffraction processes of shock waves will occur at pre-detonator exit due to the change of boundary. These periodically generated disturbance influence flow field a lot in rotating detonation combuster. Resulting in ceaselessly alternating change of detonation direction between counterclockwise and clockwise after initial process, exhibitted in figure 2 a).

Active direction control is started at 2.0 ms during the engine operating, shown in figure 2 b). Different from the ceaselessly alternating change of detonation direction in figure 2 a), the application of direction control guide a 2-counterclockwise detoantion waves mode after short transition process in annular chamber.

The active direction control method is to inject premixed reactants from the end wall of the pre-detonator while rotating detonation engine is working. In this simulation, convergent nozzle inlet boundary conditions [9] is set at the far end of pre-detonator. Premixed hydrogen/air mixture with equivalence ratio of 1, total pressure p_{inlet}= 0.5 MPa, total temperature T_{inlet}= 360 K, is injected into the 5mm height pre-detonator. Continuous filling of reactant mixture leads to the increasing length of premixed gas column in pre-detonator, as the red region rendered in figure 3 a). And when the detonation wave passes through the detonation tube outlet, a bifurcate shock wave will be transmitted into the detonation tube.

If the interface of reactant is close enough to the exit of pre-detoantor, detonation wave will be generated by the contact of incident shock wave and the reactant mixtures in pre-detonator as displayed in figure 3 c). After that, the detonation wave collide into the end wall and reflected. The reflected shock wave will propagate into combustion chamber and influence the flow field subsequently.

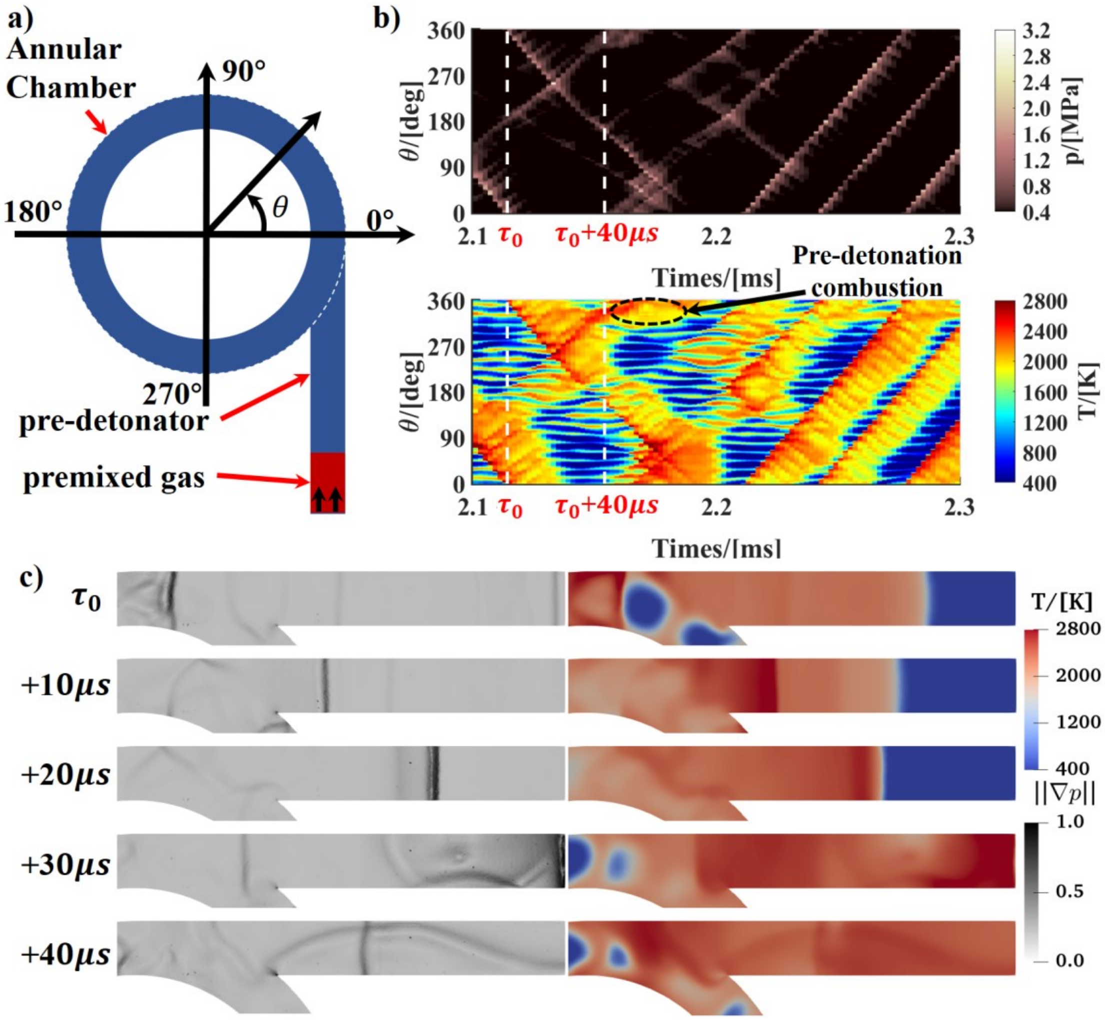


Figure 3: Mechanism of active direction control at cross-section 5 mm downstream from headwall. a) Bottom view of combustion chamber and pre-detonator. b) Detail of detonation wave mode in combustion chamber during transition process induced by direction control. c) Contour of temperature and normalized pressure gradient after τ_0 = 2.114 ms.

A pre-detonation combustion region is induced in the annular chamber by the shock wave mentioned above, as marked by black dotted ellipse in figure 3 b). The high temperature and high pressure region burn out reactant ahead of clockwise detonation wave and block the gas supply of injection orifices, extincting the clockwise detonation wave. At about 2.26 ms, two counterclockwise detonation waves appear in chamber and the purpose of direction control method is achieved. In this way, propagating direction of RDWs are regulated to the insertion direction of pre-detonator (counterclockwise). And the disturbance caused by continuous feeding of reactant mixture in pre-detonator after 2.26 ms is marked by yellow dotted rectangle in figure 2 b). Although periodic perturbation exists, the operation mode of detonation waves still sustain stable. It is convincing that, these disturbance will not destory the propagating mode in future development of rotating detonation combustor.

4 Conclusion

In this research, an active direction control method is presented and demonstrated through numerical simulation. Different from previous researches, detonation direction can be adjusted at any time when the rotating detonation combustor is working. According to the simulation result, the response time of direction control is in the order of 10^{-4} s in this structure. Due to the simple structure and flexibility of intervention moment, active direction control is of great significance for the integration of turbine and rotary detonation engine.

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