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Detonation diffraction in combustible high speed flows

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Abstract

The detonation propagation in propulsion system is affected by some factors, such as flow before detonation wave front. In this investigation, detonation propagation both upstream and downstream based on T tube were studied numerically for hydrogen/oxygen/nitrogen mixtures using Euler equation with detailed finite-rate chemistry. The fifth-order WENO scheme was adopted to capture the shock wave. Detonation enters the T tube with combustible high speed flows, and diffracts both upstream and downstream. In the downstream direction shock wave decouples from reaction zone due to rarefaction waves, and then couples again by wall reflection. In the upstream direction the detonation wave has some characteristics of oblique detonation due to compression of gas flow. So in the flow system the detonation reinitiation mechanism is categorized into two types: spontaneous reinitiation and reinitiation by reflection.

Keywords: Detonation diffraction, high speed flows, reinitiation, WENO scheme

Introduction

In contrast to the deflagration, the detonation is more efficient thermodynamically. Thus the applications of detonations in propulsion systems have been received more and more interests for many years.

For the transient characteristic of detonation waves, the key point of the detonation engine is how to make the detonation waves stay in the combustor long enough. Currently, there are three approaches to achieving this aim, and so the detonation-based engines are classified as pulse detonation engine (PDE), oblique detonation wave engine (ODWE) and rotating detonation wave engine (RDE) (Lu, 2009).

When these detonation-based engines are stable, the circumstance of detonation propagation in combustor is extremely complex, which is different with that described by the classic CJ theory. But it has been less understood so far. Compared in the quiescent mixture, detonation propagation in the flow mixture is divided into two situations: upwind propagation and downwind propagation. The investigations have been conducted experimentally (Machkenna, 1967; Ishii, 2009). The results reveal that detonation velocity is higher than CJ velocity in upwind direction and lower than CJ velocity in downwind direction. Numerical studies confirm the results again (Yi, et al, 2004; Pan et al, 2010). However, the variation mechanism is not clear. In this article, detonation propagation in flow system is investigated numerically and discussed based on model of T tube.

Physical and numerical model

Governing equations and numerical method

The two-dimensional reactive Euler equations in the non-dimensional form are given as

$$\frac{\partial Q}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=S \tag{1}$$

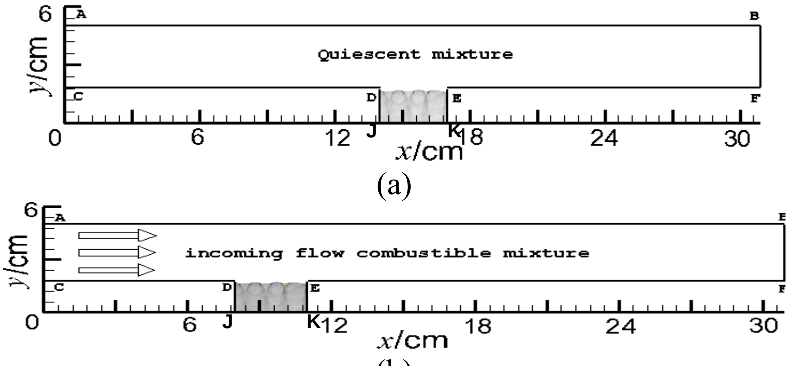
where Q denotes the variable vector, F, G, the convective flux vectors, respectively, S is the chemical source vector.

To avoid the physical oscillations and excessive numerical dissipations due to the requirements of high resolutions of the fine structures in the flow field, spatial derivatives of inviscid fluxes F and G in Eq. (1) are integrated by the fifth-order weighted essentially non-oscillatory (WENO) scheme (Jiang and Shu, 1996). The second-order additive semi-implicit Runge-Kutta method (Zhong, 1996) is employed to discretize the time and treat the stiffness of the chemical source terms.

Physical and computational configurations

The schematic of the computational model is shown in Fig. 1. In Fig. 1a, the horizontal combustor with length of 310mm and width of 32mm is connected to the vertical detonation tube with length of 18mm and width of 30mm at central location, while in Fig. 1b, at the horizontal location of 96mm. The velocity of combustible mixture is 1200m/s. The grid size is 0.1mm×0.1mm. Slip-boundary condition is given on the wall, and zero gradient condition is on the horizontal combustor exit. The stoichiometric H2/O2/Ar mixture is used, where the initial pressure and temperature are taken as 10.6KPa and 300K, respectively.

A detailed chemical reaction mechanism with 8 species and 48 elementary reactions (Oran et al, 1982) is employed for the detonation chemistry in a stoichiometric hydrogen/oxygen mixture. The reacting species include H, O, H_2, OH, H_2O, O_2, HO_2 and H_2O_2, whose thermodynamic data can be found from the JANAF table.



(a)

(b)

Figure 1. Schematic diagram of computational domain (a) quiescent system; (b) flow system.

Results and discussion

The numerical schlieren about detonation diffraction in the quiescent system are shown in Fig. 2, where the solid line is shock front and the dash line is reaction front. The detonation front doesn't reach the upper wall. The rarefaction wave created around the corner penetrates into the reaction zone and makes the reaction front decouple from the shock. There are the shocked combustible gas between the leading shock and reaction zone. The undisturbed detonation propagates with CJ velocity.

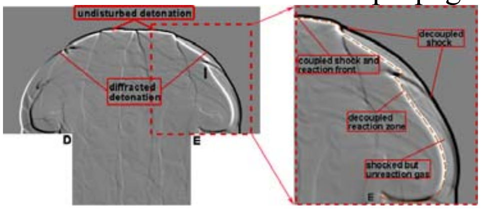


Figure 2. t=16.2μs, the numerical schlieren of detonation diffraction in the quiescent system.

The numerical schlieren about detonation diffraction in the flow system are shown in Fig. 3. During to the flow in horizontal tube (from left to right) left detonation diffraction is upstream and right detonation diffraction is downstream, which lead to obviously different characteristics. At right detonation diffraction the reaction front decouples from shock with the effect of the disturbance, which is the same as in the quiescent system. At left detonation diffraction the detonation product is compressed by the incoming flow, which is analogous to wedge compression. So the upstream diffraction front has some characteristics of oblique detonation. Steady oblique detonation consists of shock wavelets as show in Fig. 4 (Gui, 2012). The incoming flow compressed by the shock S1 is ignited by the transverse wave, thus leading to the onset of the transverse detonation TS1. As the oblique detonation wavelet D1 gradually curves downstream, its strength decreases. Finally, the decaying wave becomes a non-reactive shock wave S1.

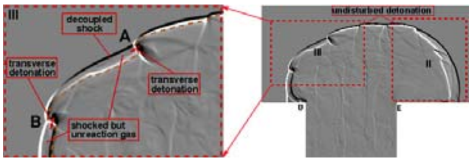


Figure 3. t=16.2μs, the numerical schlieren of detonation diffraction

in the flow system.

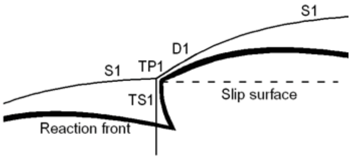
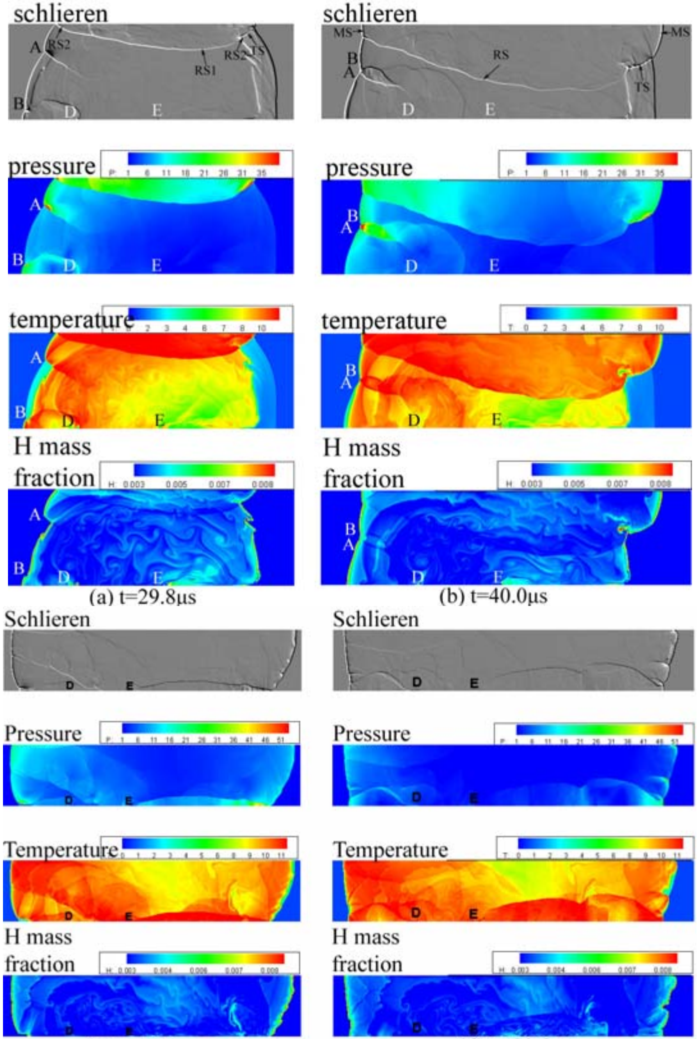


Figure 4. Schematic diagram of oblique detonation wave structure. (Gui, 2012)

So in the flow system detonation diffraction make the reaction zone decoupled from shock downstream, which tend to detonation failure, while make the wave structure similar to oblique detonation wave structure upstream, which tend to detonation self-sustaining.

The detonation wave approaches the upper wall and reflects immediately as shown in Fig. 5 which successively shows numerical schlieren, pressure, temperature and H mass fraction contours from top and bottom. The reflection of diffracted detonation wave from the upper wall is composed of two parts: normal reflection of undisturbed detonation and Mach reflection of curving shock. After reflection there are Mach stem propagating towards two sides and transverse reflection wave propagating towards the bottom wall. The strength of Mach stem is so strong as to the onset of detonation. Part of transverse reflection wave sweep the layer of pre-shocked combustible gas between the shock wave and reaction zone due to detonation decoupling downstream, which cause to transverse detonation. Therefore the whole reflection wave is the complex wave consisting of detonation wave and inertia shock wave. Through several reflections back and forth between the upper and bottom wall, there is the last formation of planar detonation in horizontal combustor. But at downstream direction there undergoes detonation failure, shock reflection, detonation reinitiation and planar detonation. At upstream direction there undergoes oblique detonation, detonation reflection and planar detonation.



(a) t=29.8μs

(b) t=40.0μs

(c) t=55.3μs

(d) t=64.6μs

Figure 5. Reinitiation event of detonation in the flow system

Conclusions

Detonation diffraction in combustible flow mixture was studied numerically based on reactive Euler equation. Detonation fails with the effect of rarefaction wave around the corner downstream. Detonation wave structure has some characteristics of oblique detonation with compression of the incoming flow upstream. Due to restriction of upper and bottom wall there is the last formation of planar detonation both upstream and downstream. But detonation reinitiation is spontaneous reinitiation upstream and reinitiation by reflection downstream.

Acknowledgments

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