Numerical Investigation of Detonation Behavior Propagating in Two-dimensional Curved Channel

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1 Introduction

The rotating detonation engine (RDE) is a new type of continuous detonation engine in that detonation always maintains its propagation in a circumferential direction of annular combustor. Some numerical simulations are conducted to reveal the characteristics of detonation in RDE [1-4]. However, in previous studies, a width of annular combustion chamber is too narrow (for example, the ratio of outer and inner radii $R_{out}/R_{in} = 1.15$ at Ref. 3 and 1.29 at Ref. 4) to study the effect of the propagation in a curved region such as diffraction and accumulation effects from inner and outer walls. For the practical use of RDE, propagation behavior of detonation in a curved region should be revealed. Several experimental studies in a curved channel have been performed [5-7] for the effect of diffraction and accumulation on detonation propagation in a curved channel. In a twodimensional curved channel, Kudo et al. [5] and Nakayama et al. [6, 7] discussed the stable propagation condition and shock front structure in curved detonation at some kinds of premixed gas composition. They showed that propagation mode is classified by the ratio of inner radius and cell width R_{in}/λ . However, the curved channel used in the previous studies is limited in a circumferential direction around 180°. In order to reveal the self-sustaining propagation mechanism of detonations in a two-dimensional curved channel, we prepared grids of two-dimensional curved channels that continue at least 2 rounds in a circumferential direction. The aim of this work is to clarify the effect of the inner radius R_{in}/λ of twodimensional curved channel at the ratio of outer and inner radii $R_{out}/R_{in} = 1.5$. We show the characteristics of unstable and stable detonation propagation depending on the size of curved channel.

2 Numerical setup

The governing equations are the compressible and reactive two-dimensional Euler equations. The fluid is an ideal gas with constant specific heat ratio of 1.4. A two-step reaction model by

Korobeinikov et al. [8] is used in the present study. This simplified model represents the reaction mechanism with two phases; induction and exothermic periods. The parameters such as activation energy of the chemical reaction model in the present work are the same as those of Inaba [9]. Premixed gas is modeled as stoichiometric hydrogen-air. Initial pressure and temperature of fresh premixed gas are fixed as 1.0 atm and 293 K, respectively.

As discretization methods, Yee's Non-MUSCL Type 2nd-Order Upwind TVD Scheme [10] is used for the spatial integration, and point-implicit method that treats only source term implicitly is used for the time integration. Figure 1 shows an initial condition and an example of the computational grids whose ratio of outer and inner radii Rout/Rin is fixed as 1.5. Computational grid is composed of straight and curved channel regions. In all calculations, at least, 8 grid points in induction reaction length L_{ind} estimated from steady solution of CJ detonation are set in all directions. In a straight tube region, more than 200 times of induction zone length of CJ detonation is adopted to avoid disturbance from the outflow boundary proposed by Gamezo et al. [11] The circumferential direction is at least more than 2 rounds and enough to observe the propagation behavior of curved detonations in a curved channel region. Inner and outer wall boundaries are adopted to adiabatic and slip conditions. The results of one-dimensional steady simulation of CJ condition are used as an initial condition, and initial shock front is located at joint of straight and curved channel as shown in Fig. 1. Parameter in the present study is normalized inner radius R_{in}/λ of 5, 10, 20, 30, 40, 50 and 60 (channel width L/ λ of 2.5, 5, 10, 15, 20, 25 and 30) in order to discuss the size of curved channel. λ denotes a cell width that is an averaged value of 1.6 mm estimated by large straight two-dimensional simulation in the present numerical method.



Fig. 1 an example of the computational grids at the ratio of outer and inner radii $R_{out}/R_{in} = 1.5$ and initial conditions.

3 Result and discussion

Two detonation modes are observed; one is stable mode at $R_{in}/\lambda = 50$ and 60 and the other is unstable mode at $R_{in}/\lambda = 5$, 10, 20, 30 and 40. The propagation characteristics of each mode do not depend on inner radius R_{in}/λ . Therefore, detailed investigations are carried out using two sets of calculation conditions; $R_{in}/\lambda = 40$ for unstable mode and $R_{in}/\lambda = 60$ for stable mode. The time evolution of the simulation results was utilized to reveal the propagation mechanism of unstable and stable modes.

Detonation propagation in a curved channel



(a) Present study $(R_{in}/\lambda = 40)$ (b) Experiment^[6] Figure 2 (a) Maximum pressure history by the present study and (b) MSOP image by Nakayama et al.^[6] of unstable mode in $R_{out}/R_{in} = 1.5$



Figure 3 (a) Maximum pressure history by the present study and (b) MSOP image by Nakayama et al.^[6] of stable mode in $R_{out}/R_{in} = 1.5$

The soot tracks on the tube were recorded in previous experimental studies [12] and showed remarkable insight for the propagation mechanism of detonations. Figure 2 shows (a) the maximum pressure history in the present study and (b) MSOP (Multi-frame Short-time Openshutter Photography proposed by Nakayama et al.^[6]) image of (a) unstable mode. Detonations propagate in a counterclockwise direction. In the case of unstable mode, both the present study and the previous experiment show that triple points by white trajectories repeat its generation and disappearance. Figure 2 clearly shows specific features of unstable mode such as re-ignition, propagation and decay of detonation. Therefore, the propagation mechanism of one cycle of unstable mode can be described using the notations 1 - 4 in Fig. 2a. (1) Small cell patterns appear, indicating the existence of a multi-headed detonation wave. Detonation maintains its propagation. (2) As detonation propagates in a circumferential direction from (1), the number of triple point decreases, and cell size expands. Soot track image becomes disturbed patterns. (3) Triple point disappears near the inner wall. This spreads or reaches to outer wall. In the case of propagation in a curved channel, diffraction effect always appears near the inner wall. In periods between (1) to (3), transverse waves, which have important roles to complete the potential exothermicity, become weak, and chemical reaction stops near the inner wall. Since its effect spreads, triple point disappears from inner wall to outer wall. (4) After that, large white belt indicating the generated transverse detonation appears near the

outer wall and propagates to inner wall as shown in Fig. 2a. Transverse detonation consumes the potential exothermicity of unburned gas pocket near inner wall. The above-described mechanism is repeated during the long period of numerical simulation in the unstable mode. Figure 3 shows (a) the maximum pressure history in the present study and (b) MSOP (Multiframe Short-time Open-shutter Photography proposed by Nakayama et al.^[6]) image of stable mode. In the case of stable mode as shown in Fig. 3, unlike unstable mode in Fig. 2, multicellular detonation always maintains its propagation. Disappearance of triple point also appears near the inner wall in a long period of the detonation propagation in Fig. 3a, but does not spread far away from inner wall. Figure 3 clearly shows specific features of stable mode such that detonation always maintains its propagation with multi-headed cellular structure. Unstable mode shows repetitions of re-ignition, propagation and decay of detonation whereas stable mode maintains the propagation of detonation. These propagation behaviors are described in order to reveal the wave structure of unstable and stable modes. Figure 4 shows six instantaneous distributions A – F of (a) density and (b) mass fraction of reactant β in the case of unstable mode at $R_{in}/\lambda = 40$. White lines in Fig. 4b denote shock fronts. Although detonations are rotating in counterclockwise direction, Fig. 4 is described at shock-attached frame. As detonation propagates in a curved channel, curved detonation front and intricate reflections of wave at outer walls behind detonation front are observed. Behind reflected shock wave on the outer wall, Mach stem structure is observed in Fig. 4. Reflection and accumulation effect on the outer wall is key point to discuss the detonation propagation in unstable mode. When detonation maintains its propagation at (A) in Fig. 4, multi-cellular curved detonation front appears. As detonation propagates from moments (A) to (B), the number of triple point decreases, which denotes gradual decay of detonation. Detonation front becomes distorted shape. Since detonation always expands near inner wall, shock wave separates from reaction front, and unburned gas pocket is generated near inner wall due to the diffraction effect. Moment (C) is just before the generation of transverse detonation near the outer wall. Transverse wave will develop to transverse detonation. In this phase, a large amount of unburned gas is observed near inner wall in Fig. 4b. At moment (D), transverse detonation is propagating to inner wall and consuming unburned gas behind shock wave. Detonation is re-ignited by transverse detonation to inner wall. At moment (E), transverse detonation reflects on inner wall and consumes all unburned gas pocket. New triple points are generated on the shock front. At moment (F), multi-cellular curved detonation maintains its propagation with decreasing the number of triple point. Flow patterns at (F) agree with those at (a) and therefore, unstable mode shows periodic behavior of decay, re-ignition and propagation.

Detonation maintains its multi-headed cellular structures in stable mode as shown in Fig. 3. We show its propagation behavior using a series of figures in order to reveal the wave structure of stable mode. Figure 5 shows six instantaneous distributions A - F of (a) density and (b) mass fraction of reactant β in the case of stable mode at $R_{in}/\lambda = 60$. White lines in Fig. 5b denote shock fronts. Although detonations are rotating in counterclockwise direction, Fig. 5 is described at shock-attached frame. As well as unstable mode, curved detonation front and intricate reflections of wave at outer walls behind detonation front are observed. Transverse wave consumes premixed gas behind detonation front at (A) – (C), a curved detonation maintain its propagation. At moment (D), diffraction effect makes transverse wave weak, and chemical reaction stops near inner wall. Unburned gas exists near the inner wall. Unlike unstable mode, it does not spread far away from inner wall, and curved detonation at outer side of channel always propagates with multi-cellular structure. At moment (E), transverse

detonation reflects on the wall. At moment (F), cellular structure near the inner wall is generated. As detonation propagates in a two-dimensional curved channel, diffraction effect is also observed in the stable mode, but is relatively small for detonation propagation. This indicates that detonation becomes stabilized at larger R_{in}/λ , which agrees with the experimental results [5-7].

4 Conclusion

Detonations with curved shock front propagating in a curved channel were numerically investigated using two-dimensional Euler equations and two-step reaction model by Korobeinikov et al. This paper focuses on the effect of the size of a two-dimensional curved channel on the propagation behavior. We simulated the detonation with various channel widths R_{in}/λ at which the ratio of inner and outer radii (R_{out}/R_{in}) are 1.5. Two propagation modes, namely unstable and stable modes, are observed depending on inner radius R_{in}/λ . Soot track images in the present study agreed well with those by the previous experimets. In unstable mode at $R_{in}/\lambda = 5$, 10, 20, 30 and 40, diffraction and accumulation effect from inner and outer wall complexly appear in detonation propagation. Chemical reaction near inner wall is inhibited by the diffraction effect. As channel width is small, diffraction effect spread from inner to outer wall, and detonation temporally decays. After some time, transverse detonation is generated and consumes unburned gas pocket near inner wall. A curved detonation of unstable mode propagates with repetition of decay, re-ignition and propagation. In stable mode at $R_{in}/\lambda = 50$ and 60, diffraction effect is also observed as well as in unstable mode. However, it is relatively small, and the detonation propagates steadily with keeping a curved multi-cellular shock front structure. This indicates that detonation becomes stabilized at larger R_{in}/λ , which agrees with the experimental results.

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Fig. 4 Instantaneous distributions A – F of (a) density and (b) mass fraction of reactant in the case of unstable mode at $R_{in}/\lambda = 40$

Fig. 5 Instantaneous distributions A – F of (a) density and (b) mass fraction of reactant in the case of stable mode at $R_{in}/\lambda = 60$