Study on Detonation Waves propagating through Curved Channels

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1 Introduction

Stable detonation wave propagation in an annular combustor is required for a Rotating Detonation Engine (RDE) [1-3], known also as a Continuous Detonation Wave Engine. For the purpose of RDE design, it is important that the conditions for stable detonation wave propagation in a curved channel, which is a basic element of an annular combustor, be well understood. Interests are focused on the detonation wave propagation through a curved channel also in the field of safety engineering [4, 5]. Since the detonation wave propagating through a complex pipe system acts a major dynamic load on a pipe structure [6], the prediction of the detonation propagation characteristics in a curved channel is important in that field.

Several experimental studies on the detonation waves propagating through curved channels have been conducted in the past [7-9]. However, the detonation propagation phenomenon has not yet been sufficiently understood due to its complexity. In order to examine the detonation wave propagating through a curved channel, visualization experiments were performed in this study. The wave front motion and triple point trajectories of the detonation waves propagating though curved channels were simultaneously visualized by using a new method. This paper outlines the results of the experiments.

2 Multi-frame short-time open-shutter photography

A new visualization method that enable one to observe simultaneously the wave front motion and triple point trajectories of a detonation wave was developed in the present study. Such a simultaneous observation is absolutely necessary for understanding the detonation propagation phenomenon in a curved channel. Useful data such as detonation cell width, wave front shape, detonation propagation velocity, quench/re-initiation process of detonation, and so on, are obtained at a time using this visualization method.

Short-time Open-shutter Photography (SOP) makes it possible to record simultaneously detonation wave front positions and triple point trajectories. The concept of SOP is shown in Fig. 1. A detonation wave is propagating through a curved channel from lower right to upper left in Fig. 1. By limiting exposure time to a few microseconds, only the triple point trajectories within the area swept by

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detonation wave front are recorded in the exposure time. The forward or backward edges of the triple point trajectories recorded in the SOP image give the detonation wave front shape. The influence of the luminescence of burned gas caused by reflected shocks can also be minimized in the SOP image by setting the exposure time appropriately.

By performing SOP for each individual frame of a high-speed camera, the overall triple point trajectories in a curved channel can be visualized by superimposing these SOP images and the variation in wave front motion also be observed using the superimposed image. This new visualization method is named Multi-frame Short-time Open-shutter Photography (MSOP) in the present study.

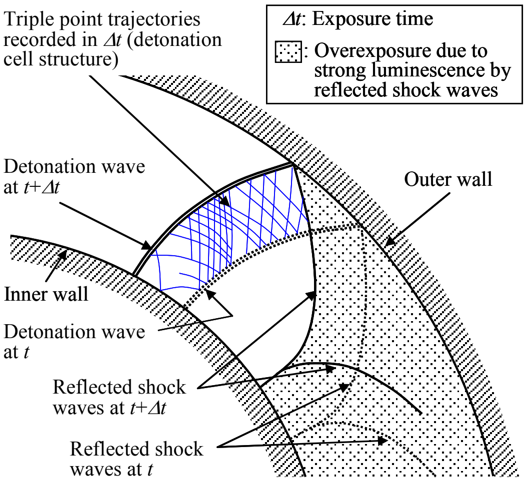

Figure 1. Schematic illustrating the concept of SOP.

3 Experimental setup and conditions

The schematics of the curved channels and observation chamber used in the present study are shown in Fig. 2. Five types of curved channels with different inner radii of curvature (5 mm, 10 mm, 20 mm, 40 mm, and 60 mm) were used. The inner/outer radii of curvature within the curved sections of the curved channels are maintained constant. The cross-section shape of the channels is rectangular. The wave front of the detonation wave propagating through the rectangular cross-section tube (20 mm in width and 16 mm in depth) which is located immediately above the Shchelkin spiral is partially cut out and introduced into the channel. As the depth of the channels is so thin (1 mm), the structure of the detonation wave in the channel becomes two-dimensional. Thus, the triple point trajectories can be recorded clearly by MSOP.

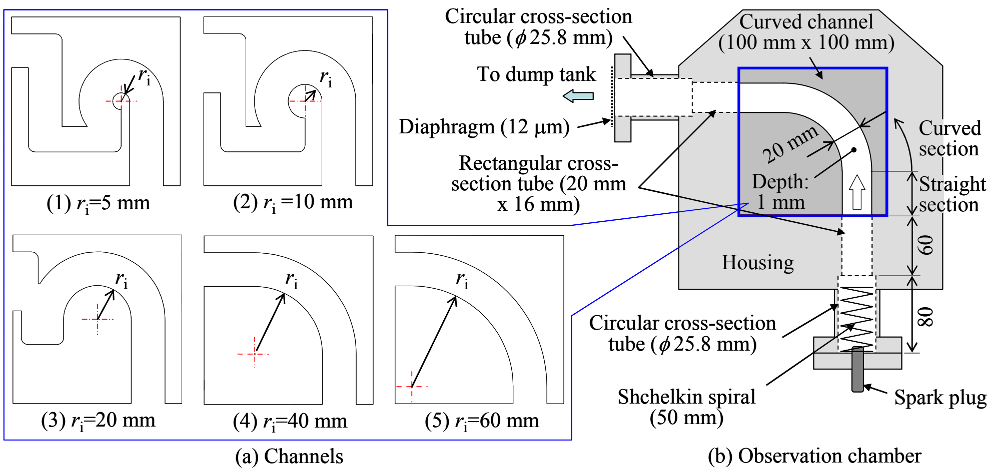

Figure 2. Schematic of the channels and observation chamber.

Shimadzu HPV-2 high-speed video camera was used to visualize the detonation waves propagating through the curved channels. All the images were taken at 4 μs time intervals in each experiment. The spatial resolution of the images is approximately 0.3 mm.

A stoichiometric ethylene-oxygen mixture gas was used in the present study. The mixture gas is filled at a given pressure into the observation chamber in which the air is evacuated. The range of the filling pressure is from 20.0±1.0 kPa to 80.0±1.0 kPa and the mixture gas is filled at room temperature. The experimental conditions are summarized in Table. 1.

Table 1: Experimental conditions

Shot No.	Filling pressure, p_0 [kPa]	Temp. [K]	Inner radius, r_i [mm]	Cell width, λ [mm]	Propagation mode	Shot No.	Filling pressure, p_0 [kPa]	Temp. [K]	Inner radius, r_i [mm]	Cell width, λ [mm]	Propagation mode
01	21.0	297-299 Room temp.	5	2.3	Unstable	20	50.3	297-299 Room temp.	20	0.9	Critical
02	31.0		5	1.5	Unstable	21	60.3		20	0.7	Critical
03	41.0		5	1.1	Unstable	22	70.3		20	0.6	Stable
04	51.0		5	0.9	Unstable	23	20.8		40	2.4	Unstable
05	61.0		5	0.7	Unstable	24	25.8		40	1.8	Critical
06	70.6		5	0.6	Unstable	25	31.5		40	1.5	Critical
07	80.6		5	0.5	Unstable	26	36.5		40	1.2	Stable
08	21.0		10	2.3	Unstable	27	40.8		40	1.1	Stable
09	31.0		10	1.5	Unstable	28	50.8		40	0.9	Stable
10	41.0		10	1.1	Unstable	29	60.8		40	0.7	Stable
11	51.0		10	0.9	Unstable	30	70.6		40	0.6	Stable
12	61.0		10	0.7	Unstable	31	20.8		60	2.4	Critical
13	70.6		10	0.6	Critical	32	26.5		60	1.8	Stable
14	80.6		10	0.5	Critical	33	28.5		60	1.7	Stable
15	20.3		20	2.4	Unstable	34	30.8		60	1.5	Stable
16	30.3		20	1.5	Unstable	35	40.8		60	1.1	Stable
17	36.5		20	1.2	Unstable	36	50.8		60	0.9	Stable
18	40.3		20	1.1	Unstable	37	60.8		60	0.7	Stable
19	45.3		20	1.0	Unstable	38	70.8		60	0.6	Stable

4 Experimental results

4.1 Detonation propagation characteristics in a curved channel

It was verified that the detonation waves propagating through the straight sections of the curved channels were quite planar. Figure 3 shows the measurement results of the velocities of the planar detonation waves in the straight sections (D_{str}). The symbols represent the measured values and the solid line represents the CJ detonation velocity (D_{CJ}) calculated using CEA [10]. The error bars represent possible systematic errors of the measurements. All the values of measured D_{str} were approximately 5% lower than D_{CJ}. This velocity deficit was considered to have been caused by momentum loss due to the thin depth of the curved channels.

The normal detonation velocity on the inner wall of a curved channel ($D_{n,i}$) was measured from the alternation of the forward edge position of the luminescence region on the inner wall as determined using the MSOP image. The propagation of the detonation wave through a curved channel was categorized based on how high $D_{n,i}$ was. The typical variations in $D_{n,i}$ are shown in Fig. 4. The values of $D_{n,i}$ are nondimensionalized by D_{str} in Fig. 3. θ_i is the angle from the origination of the curved section to the detonation wave front on the inner wall. The error bars represent typical possible systematic errors of the measurements. In the present study, the propagation mode that consistently satisfies the relation of $D_{n,i}/D_{str} \geq 0.8$ is defined as the stable mode, the mode that cannot satisfy the relation of $D_{n,i}/D_{str} \geq 0.8$ but can consistently satisfy the relation of $D_{n,i}/D_{str} \geq 0.6$ is defined as the critical mode, and the mode in which $D_{n,i}/D_{str} < 0.6$ even just once is defined as the unstable mode. As shown in Fig. 4, the variation range of $D_{n,i}/D_{str}$ is narrow in the case of the stable mode, however that is wide in the case of the critical and unstable mode.

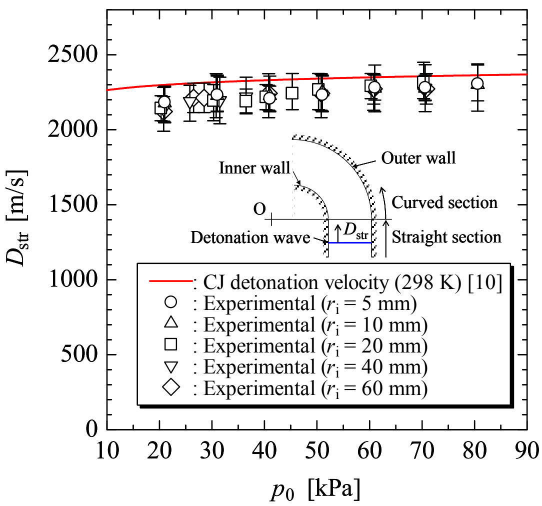

Figure 3. Velocity of the planar detonation wave propagating through the straight section of a curved channel.

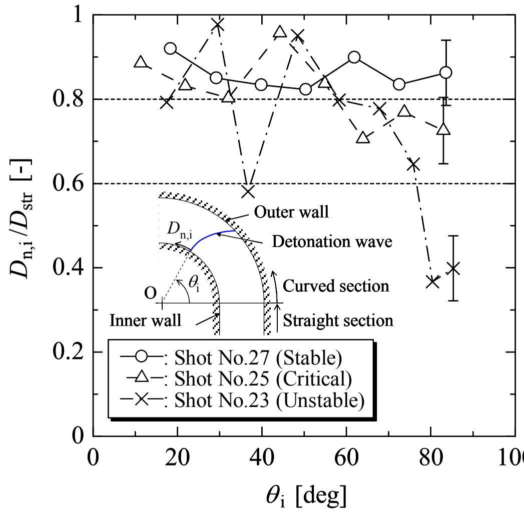

Figure 4. Typical variations in the normal detonation velocities on the inner wall of the curved channel (r_i = 40 mm).

The typical MSOP images taken at a given r_i (r_i = 40 mm) are shown in Fig. 5. The images in Fig. 5 were taken in the same experiments represented in Fig. 4. Fig. 5(a) corresponds to the stable mode, Fig. 5(b) to the critical mode, and Fig. 5(c) to the unstable mode. The arrows in these figures indicate the direction of detonation wave propagation. At a given r_i, a higher p_0 makes the detonation wave in a curved channel more stable.

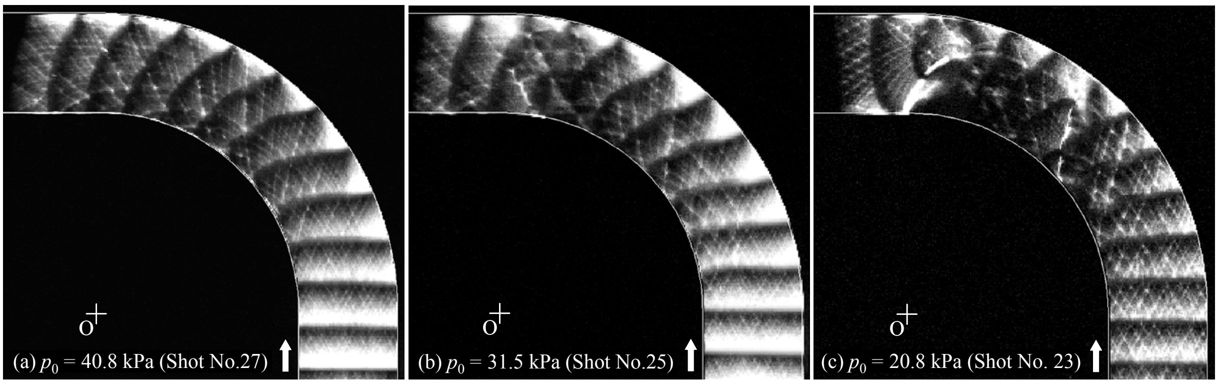

Figure 5. Typical MSOP images at a given inner radius of a curved channel (r_i = 40 mm).

The detonation cell in the vicinity of the inner wall of the curved channel is enlarged soon after the detonation wave enters the curved section of the channel due to the expansion waves from the inner wall as shown in Fig. 5(a). When the cell has enlarged, new cells are generated smoothly within the enlarged cells in the vicinity of the inner wall. The smooth detonation wave front can be maintained consistently in the stable mode due to this smooth cell generation. The detonation wave propagates while maintaining a specific shape, and the interval of the detonation wave front recorded in the MSOP image is constant within θ_i = 45-90 deg.

A collapse of the detonation cell structure occurs in the unstable mode. A temporary collapse of the detonation cell structure is observed in the vicinity of the inner wall around θ_i = 35 deg in Fig. 5(c). Although the detonation cell structure in the vicinity of the inner wall is recovered from around θ_i = 45 deg by generation of the new fine cells, the detonation cell structure collapses completely within θ_i = 70-90 deg. The shape of detonation wave front is fluctuating and the detonation wave front is not smooth.

The critical mode looks like the intermediate stage between the unstable mode and the stable mode as shown in Fig. 5(b).

The typical MSOP images taken at a given p_0 (p_0 = 31.0±1.0 kPa) are shown in Fig. 6. Fig. 6(a) corresponds to the stable mode, Fig. 6(b) to the critical mode, and Figs. 6(c)-(e) to the unstable mode. At a given p_0, a larger r_i makes the detonation wave more stable. That is to say, the increase of r_i has the same effect as the increase of p_0 on the stability of the detonation wave in a curved channel.

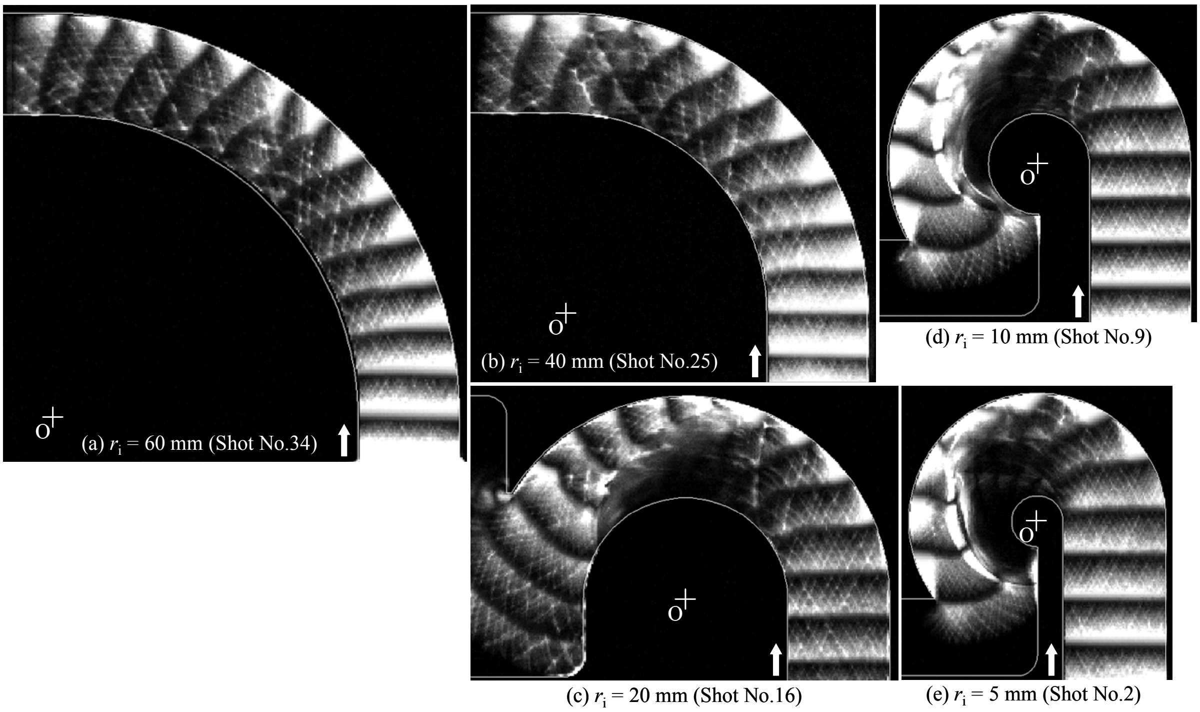

Figure 6. Typical MSOP images at a given filling pressure of mixture gas (p_0 = 31.0±1.0 kPa).

4.2 Condition of stable detonation propagation in a curved channel

The radius of inner wall of curved channel and detonation cell width are the characteristic lengthes of a curved channel and of detonability of a mixture gas, respectively. The relation of r_i and λ in terms of the detonation propagation mode is shown in Fig. 7. In the present study, no stable propagation mode was observed below the line of $r_i/\lambda = 21$ and detonation propagation became stable consistently above the line of $r_i/\lambda = 32$. Therefore, the propagation mode of the detonation wave propagating through a curved channel is considered to transition to the stable mode from the unstable mode within $21 \leq r_i/\lambda \leq 32$ under the conditions of the present study.

5 Conclusions

The front shock shapes and the trajectories of triple points of the detonation waves propagating through the curved channels were simultaneously observed using Multi-frame Short-time Open-shutter Photography (MSOP). The ratio of the inner radius of curved channel (r_i) to the normal detonation cell width (λ) was an important factor determining the stability of the detonation propagation in a curved channel. The critical condition under which the propagation mode of the detonation wave transitioned from unstable to stable is having r_i equivalent to 21 to 32 times λ. In the stable mode, a detonation wave propagates through a curved channel while maintaining a specific wave front shape and the smooth detonation wave front can be maintained consistently. Although the detonation cell in the vicinity of the inner wall of the curved channel is enlarged due to the expansion waves from the inner wall, new detonation cells are generated smoothly within the enlarged cells and the cell structure can be maintained. However, a collapse of the detonation cell structure occurs in the unstable mode. The shape of detonation wave front is fluctuating and the detonation wave front is not smooth.

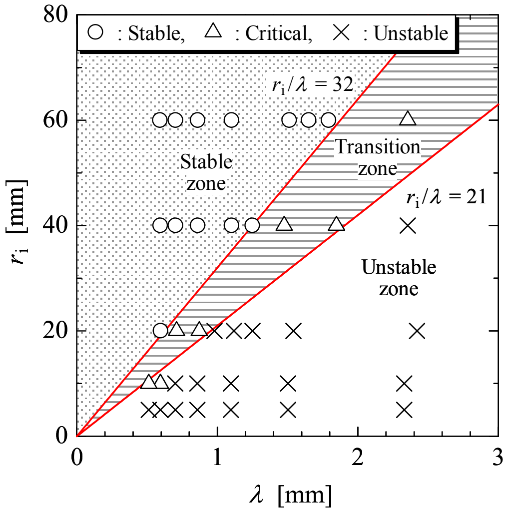

Figure 7. Relation between the inner radius of the curved channel and the normal detonation cell width in terms of the propagation mode.

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