Research paper

Experiments on detonation initiation and propagation in extremely thin channels

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Abstract

Initiation and propagation characteristics of detonations in extremely thin channels were experimentally studied using a soot-foil-pattern technique. In the experiments, we used stoichiometric propane-oxygen-nitrogen and hydrogen-oxygen-nitrogen gas mixtures, where dilution ratio was varied as a governing parameter. A thin channel, whose height was varied as another governing parameter, was installed inside a large reaction chamber. The reaction chamber was filled with a premixed gas mixture at the ambient conditions of temperature and pressure, and the gas mixture was ignited on an inner wall of the reaction chamber. When a flame went into the thin channel, a detonation was initiated in the thin channel in some conditions. Especially, in some highly-diluted conditions, a detonation was initiated in the thin channel whereas no detonation was initiated outside the thin channel in the reaction chamber. In the conditions near the limit of detonation initiation, peculiar soot-foil patterns were observed for hydrogen-oxygen-nitrogen gas mixtures, which showed unstable double cellular structure.

Keywords : detonation, initiation, thin channel, double cellular structure

1. Introduction

The degree of easiness of detonation initiation and propagation in confined geometries is important for safety issues. Especially, detonation initiation by deflagration-to-detonation transition (DDT) should be comprehensively studied because a detonation is initiated with small ignition source energy through this process. In circular-cross-section tubes, the distance required for DDT is generally smaller for smaller-diameter tubes[1]. However, when the diameter of a tube is too small, frictional and thermal losses at the side wall make detonation propagation difficult[2), 3)]. Although the studies on detonation initiation and propagation in circular-cross-section tubes were well carried out, rectangular-cross-section channels are sometimes more important for safety issues because actual confined geometries important for safety issues are, in many cases, interspaces between a floor, a ceiling, walls, and shelves, and their cross section is rectangular. Detonations in narrow rectangular-cross-section channels have also been studied so far[4)−6)]. However, previous studies on detonations in narrow rectangular-cross-section channels are mainly not on initiation but on propagation, and therefore, we have limited knowledge on initiation characteristics of detonations in narrow rectangular-cross-section channels.

In this paper, we report an experimental study of detonations in narrow rectangular-cross-section channels mainly on their initiation characteristics. The rectangular-cross-section channels we used were so thin that their heights were smaller than the detonation cell width, which is the transverse characteristic length of a detonation front. Therefore, the detonation front we investigated must be two dimensional. In order to investigate detonation initiation in a channel, a flame was ignited outside the channel, and the flame propagated into the channel. For diagnosing detonation initiation and propagation in the extremely thin channels, the soot-foil-pattern technique was used.

2. Experimental arrangement

Figure 1 shows the experimental arrangement. A rectangular-cross-section channel, which we call the thin channel hereafter, was installed inside a large reaction chamber. The dimension of the reaction chamber was 200 mm x 1020 mm x 50 mm. Details of the thin channel are shown in Fig. 2. The thin channel consisted of two rigid duralumin plates, whose dimension was 900 mm x 200 mm, and thin spacers. The thickness of the spacers was 0.5, 1, or 2 mm. One of the inner surfaces of the duralumin plates was coated with soot for recording soot tracks produced by a detonation front. Another soot plate was installed on the outside wall of the thin channel in order to investigate detonation initiation outside the thin channel in the reaction chamber. The reaction chamber was filled with a premixed detonable gas mixture at the ambient conditions of temperature and pressure. We used nitrogen-diluted stoichiometric propane-oxygen gas mixtures ($C_3H_8+5O_2+\beta N_2$) and nitrogen-diluted stoichiometric hydrogen-oxygen gas mixtures ($2H_2+O_2+\beta N_2$), where β was the parameter representing the dilution ratio. In the experiments, the parameter β was varied as a governing parameter. Another governing parameter was the height of the thin channel (h), i.e., the thickness of the spacers. Figure 3 shows the cell width for $C_3H_8+5O_2+\beta N_2$ and $2H_2+O_2+\beta N_2$ obtained in preliminary experiments where a soot foil was installed on the side wall of a circular tube whose inner diameter was 100 mm. We restricted the experimental conditions so that the height of the thin channel, h, was smaller than the cell width of the detonations shown in Fig. 3. The premixed detonable gas mixture in the reaction chamber was ignited by two automotive spark plugs, which were installed at one end of the reaction chamber as shown in Fig. 1. Another end of the reaction chamber was connected to a damp tank through a diaphragm of a polymer film of 125 μm in thickness.

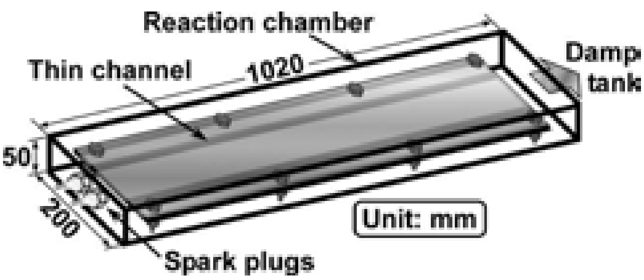

Fig. 1 A thin channel installed inside a reaction chamber.

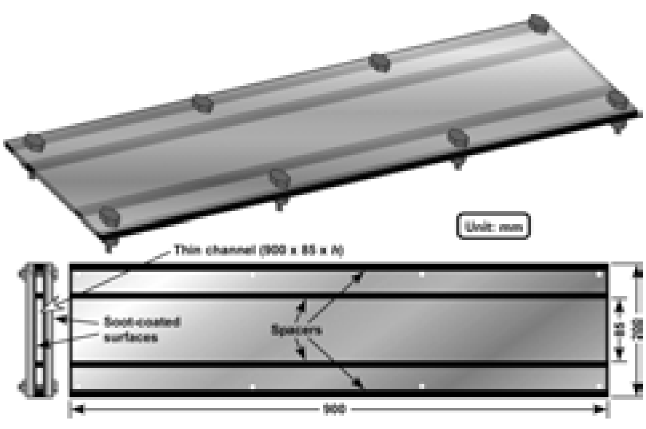

Fig. 2 Details of the thin channel.

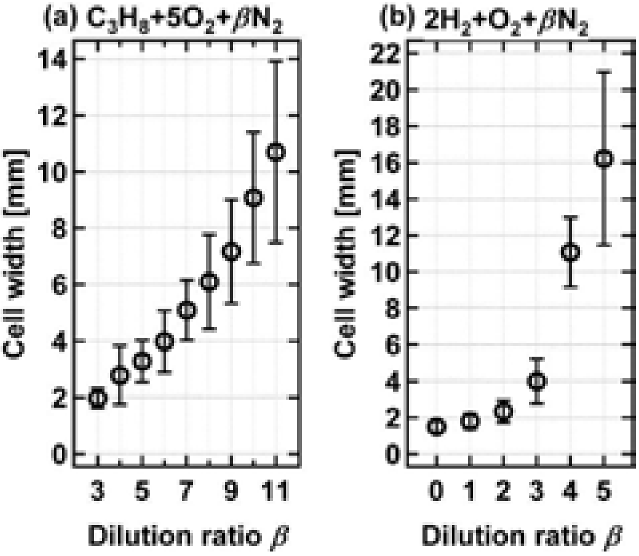

Fig. 3 Cell width measured in a 100-mm-diameter circular tube. (a) $C_3H_8+5O_2+\beta N_2$. (b) $2H_2+O_2+\beta N_2$.

3. Results and discussions

3.1 Detonation initiation in thin channels

Figure 4(a) summarizes the experimental results on detonation initiation for the mixtures $C_3H_8+5O_2+\beta N_2$, and Fig. 4(b) summarizes those for the mixtures $2H_2+O_2+\beta N_2$. The circles represent the cases where a detonation was initiated and propagated from the ignition side toward the damp-tank side. The squares represent the cases where two detonations were initiated at two locations and propagated in opposite directions. In these cases, two detonations propagating in opposite directions collided with each other in a thin channel. The triangles represent the cases where a detonation was initiated far from the spark plugs and propagated from the damp-tank side toward the ignition side, that is, in the backward direction. The crosses represent the cases where no detonation was initiated. In the experimental conditions for which multiple symbols were plotted, different results were obtained in repeated experiments. Details of the observed modes are explained below.

Figure 5 shows a typical soot-foil record for the cases plotted by circles in Fig. 4. In this case, a detonation was initiated in the middle part of the thin channel, and propagated from the ignition side toward the damp-tank side. As shown in Fig. 5, the detonation was unstable, but continuously propagated up to the exit. Figure 6 shows a typical soot-foil record for the cases plotted by triangles in Fig. 4. In this case, a detonation was initiated near the exit (the damp-tank side), propagated toward the ignition side, and was extinguished in the middle part of the thin channel because the mixture near the ignition side had already been burned. The detonation-initiation location is magnified in Fig. 7. The detonation was initiated near the spacer plate, and propagated in the backward direction. The cases shown by squares in Fig. 4 are something like

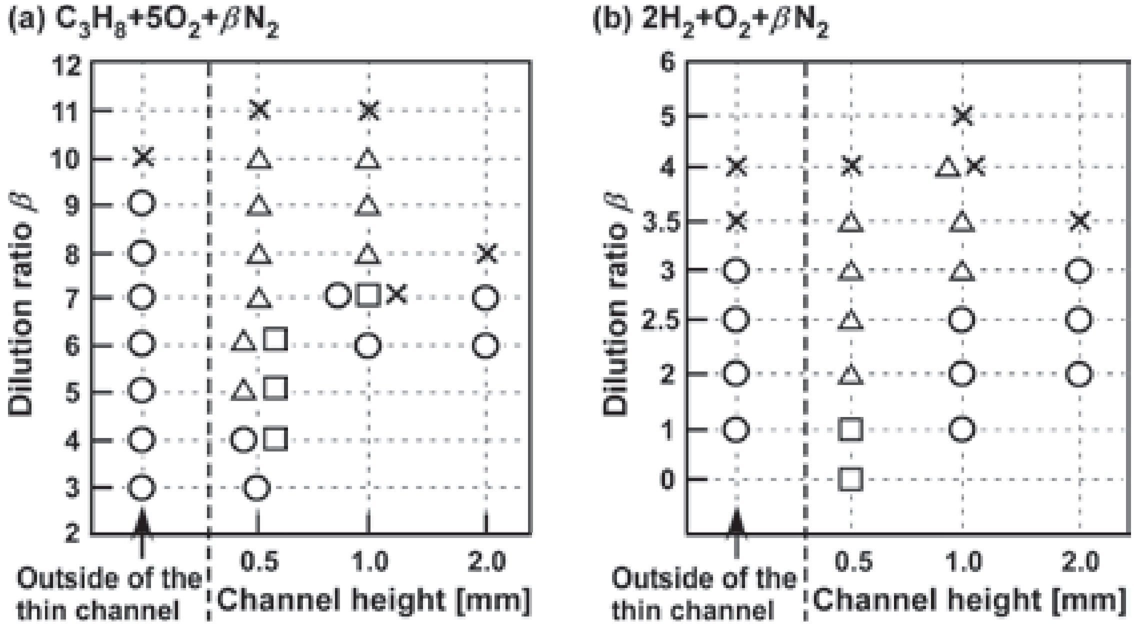

Fig. 4 Summary of the results on detonation initiation. (a) $C_3H_8+5O_2+\beta N_2$. (b) $2H_2+O_2+\beta N_2$.
○ : A detonation propagated in the forward direction (from the ignition side to the damp−tank side).
△ : A detonation propagated in the backward direction (from the damp-tank side to the ignition side).
□ : Two detonations propagated in both directions and collided with each other.
× : No detonation was initiated.

Fig. 5 Typical soot-foil record (85 mm x 900 mm) for the cases plotted by circles in Fig. 4.

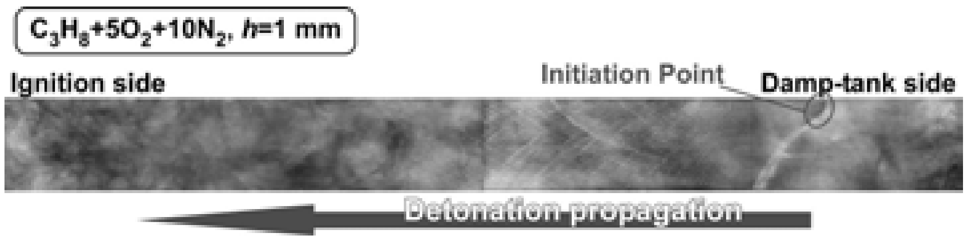

Fig. 6 Typical soot-foil record (85 mm x 900 mm) for the cases plotted by triangles in Fig. 4.

the combination of the cases shown in Figs. 5 and 6, and a typical soot-foil record is shown in Fig. 8.

It is very interesting that detonations are initiated near the exit and propagate in the backward direction when the thin-channel height is small and the gas mixture is highly diluted. This phenomenon is interpreted as follows. A subsonic flame inside the thin channel propagates much slower than the flame propagating outside the thin channel because of heat loss. Therefore, when a forward-directed detonation is not initiated in the thin channel, a flame enters the thin channel from the exit before detonable gas mixture inside the thin channel burns out. In such situation, the backward-directed flame in the thin channel propagates in a detonable gas mixture highly disturbed by compression waves created by the forward-directed flame, and is easy to make a transition to a backward-directed detonation.

From the viewpoint of safety issues, it is noteworthy that detonations were initiated inside the thin channels whereas no detonation was initiated outside when h=0.5,1 mm for the mixture $C_3H_8+5O_2+10N_2$, h=0.5, 1 mm for the mixture $2H_2+O_2+3.5N_2$, and h=1 mm for the mixture $2H_2+O_2+4N_2$. Generally, detonations are hard to propagate in narrow spaces because of momentum and heat losses. However, open-ended thin channels sometimes promote detonation initiation. These results suggest higher risks of detonation initiation in open-ended narrow gaps rather than in wide spaces.

3.2 Influence of the exit condition of thin channels on detonation initiation

In order to examine the above-mentioned mechanism of the backward propagation of detonations in the thin channels, we carried out additional experiments using thin

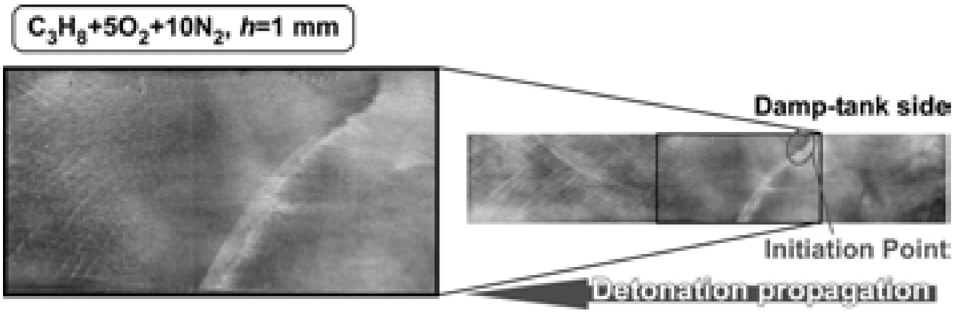

Fig. 7 Magnified view of the detonation-initiation location of the soot-foil record shown in Fig. 6.

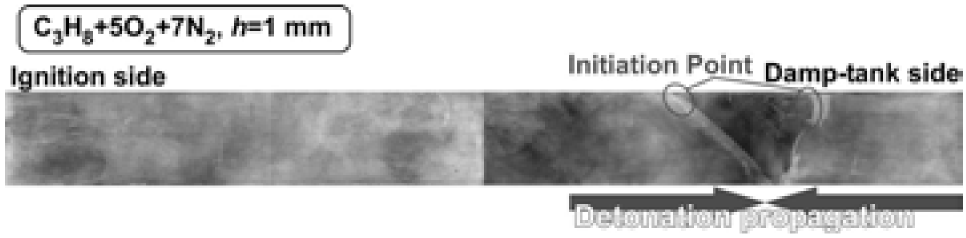

Fig. 8 Typical soot-foil record (85 mm x 900 mm) for the cases plotted by squares in Fig. 4.

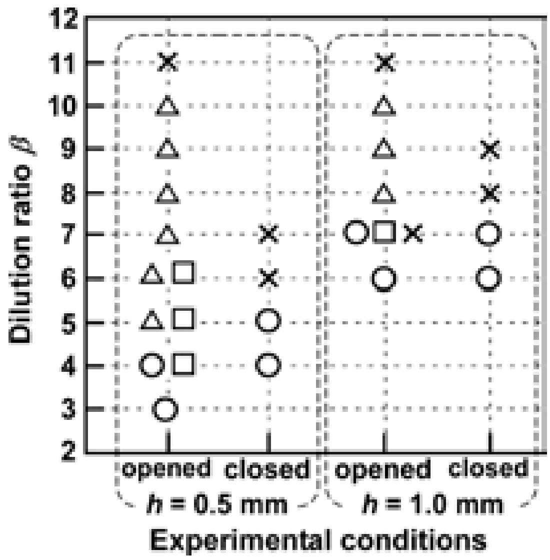

Fig. 9 Influence of the exit condition on the detonation initiation inside the thin channels for $C_3H_8+5O_2+\beta N_2$.

channels with the exit closed. Figure 9 shows the comparison between the results for the exits opened and closed. In the horizontal axis, "closed" represents the results for the thin channels with the exit (damp-tank side) closed, and "opened" represents the results for those with the exit opened, which are the same as shown in Fig. 4(a). The meanings of the symbols are the same as those in Fig. 4. As shown in Fig. 9, no backward propagation of detonations was observed for the thin channels with the exit closed. This supports the interpretation described above.

3.3 Double cellular structure

For the mixtures $2H_2+O_2+\beta N_2$, some peculiar soot-foil patterns were observed. In this subsection, we report such soot-foil patterns. Figure 10 shows a soot foil record obtained in the case of $2H_2+O_2+2N_2$ and h=0.5 mm. As shown in Fig. 10(a), a strong triple point ran from top right corner toward the lower left with branching. Inside the relatively large scale soot-foil pattern depicted by such strong triple points, rather weak smaller cellular patterns can be observed. Such rather weak smaller cellular patterns gradually disappeared. The rather weak smaller cellular patterns appeared again as shown in Fig. 10(b). That is, double cellular structure was observed although it was not stable. Strong triple points disappeared between the regions b and c, and appeared again in the region c like a galloping detonation. After strong triple points re-appeared, the rather weak smaller cellular patterns appeared again as shown in Fig. 10(c). Although double cellular structure was observed, the unstable propagation of the detonation seemed to be sustained by the strong triple points only.

Figure 11 shows a soot foil record obtained in the case of $2H_2+O_2+3N_2$ and h=0.5 mm. As shown in Fig. 11, a detonation was initiated at about a quarter from the exit (the damp-tank side), and propagated toward the ignition side. After the detonation was initiated, a strong triple point was branched into two, and the detonation propagated in the two-headed mode. However, one of two strong triple points disappeared in the middle part of the thin channel, and the detonation propagated in the single-headed mode. As shown in Fig. 11(a), small cellular structure was observed at the right-hand side of the path of the strong triple point which ran from the top right corner to the lower left. This small cellular structure was depicted by a transverse detonation. Such a transverse detonation accompanying a single-headed detonation has been well known since several decades ago[7]. As shown in Fig. 11(b), some almost parallel triple-point tracks were observed at the left-hand side of the path of the strong triple point. A similar soot-foil record was recently reported by Stamps, Slezak, and Tieszen[8]. The soot-foil pattern observed at the left-hand side of the path of the strong triple point is interpreted as follows. A transverse detonation wave propagated downward along the vertical

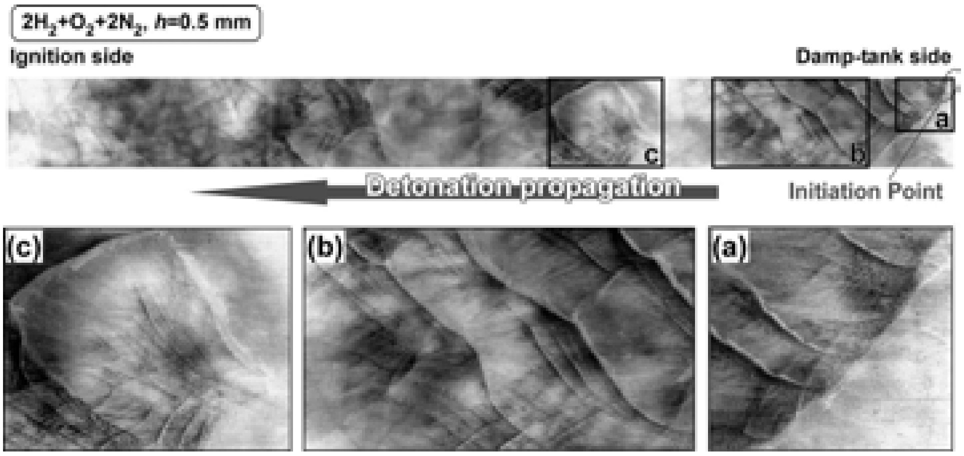

Fig.10 Soot foil record obtained in the case of $2H_2+O_2+2N_2$ and h=0.5 mm.
Top : Whole view of the soot-foil record (85 mm x 900 mm). (a) Magnified view of the region a. (b) Magnified view of the region b. (c) Magnified view of the region c.

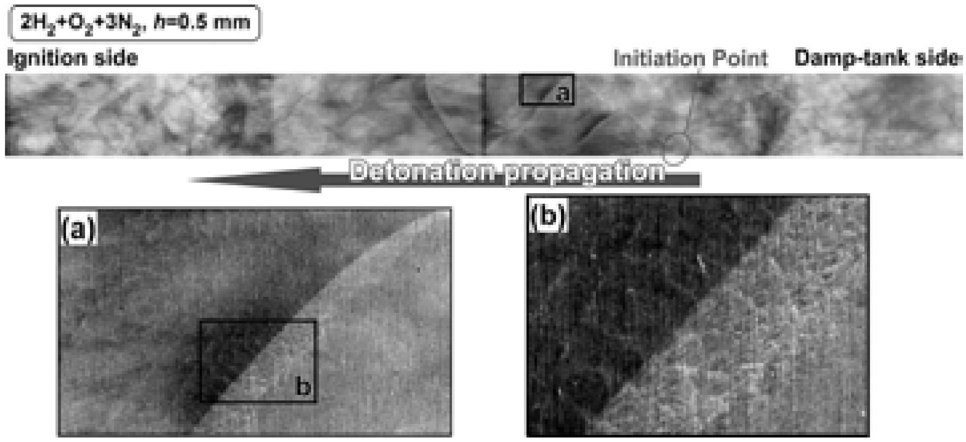

Fig.11 Soot foil record obtained in the case of $2H_2+O_2+3N_2$ and h=0.5 mm.
Top : Whole view of the soot-foil record (85 mm x 900 mm).
(a) Magnified view of the region a. (b) Magnified view of the region b.

front of the leading shock wave propagating from right to left. And transverse shock waves propagated along the front of the transverse detonation wave. When such a transverse shock wave was reflected at the intersection of the leading shock wave and the transverse detonation wave, namely the strong triple point, a part of the transverse shock wave was transmitted into the left side of the strong triple point, and propagated as a transmitted diverging shock wave like a cylindrical blast wave. The soot-foil pattern observed at the left-hand side of the path of the strong triple point was depicted by the intersections of these transmitted diverging shock waves and the vertical leading shock wave. The rather weak smaller cellular patterns inside the large scale soot-foil pattern depicted by the strong triple points seemed to be triggered by these transmitted shock waves.

4. Conclusions

We carried out experiments on detonation initiation and propagation in extremely thin channels for mixtures of $C_3H_8+5O_2+\beta N_2$ and $2H_2+O_2+\beta N_2$ by using a soot-foil-pattern technique. When the height of a channel was much smaller than the cell width, it was found that a detonation propagated unstably in the thin channel even if it was initiated. When the gas mixtures were highly diluted, such an unexpected phenomenon was observed that a detonation was initiated near the exit of an open-ended thin channel and propagated in the backward direction. And in some of such cases, a detonation was initiated in a thin channel whereas no detonation was initiated in a wide space outside the thin channel. The key to initiation of the backward-directed detonation was a flame entering the thin channel from the exit. This suggests that a narrow gap with both ends open is sometimes more dangerous than wide spaces. Further, in the conditions near the limit of detonation initiation, peculiar soot-foil patterns were observed for hydrogen-oxygen-nitrogen gas mixtures, which showed unstable double cellular structure.

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非常に狭い隙間におけるデトネーションの起爆・伝播に関する実験

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非常に狭い隙間におけるデトネーションの起爆・伝播特性を，すす膜法を用いて実験的に研究した．実験では，プロパン－酸素－窒素量論混合気および水素－酸素—窒素量論混合気を用い，支配パラメータの一つとして，窒素希釈率を変化させた．また，もう一つの支配パラメータとして，２次元実験容器の隙間高さを変化させた．実験では，２次元実験容器を大きな実験チェンバーの中に設置し，実験チェンバー全体に予混合可燃性混合気を常温・常圧で充填し，実験チェンバーの側壁上で混合気に点火した．非常に狭い隙間に火炎を進入させた場合，ある条件では隙間内でデトネーションが起爆することがわかった．特に，窒素希釈率が高い場合において，狭い隙間の外の実験チェンバー内ではデトネーションが起爆せず，隙間内でのみデトネーションが起爆する場合があることがわかった．また，水素－酸素－窒素混合気の場合において，デトネーションの起爆限界付近の条件では，不安定な２重構造のセル模様が観測された．

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