Critical Condition for Detonation Diffraction with Stable and Unstable Mixtures

Jiro Kasahara and Akira Kawasaki
Nagoya University
Nagoya, Aichi 464-8673, Japan

1 Introduction

When a planar detonation wave emerges from a tube into unconfined space filled with a gas mixture, detonation wave diffraction may occur due to an abrupt change in the cross-sectional area. When this happens, the shape of the detonation wave changes from a plane to a curve. The shock wave constituting the detonation wave is attenuated by the expansion waves generated from the apex of the tube exit, and thus the shock wave is decoupled from the reaction front. As described by Zeldovich [1], in the case when the tube diameter is smaller than the critical tube diameter, the reaction front is decoupled from the shock front completely, and the detonation wave should not propagate into the unconfined space. However, in the case when the tube diameter is larger than the critical tube diameter, a local explosion may occur at the wave front, and then a new wave front would be generated and the detonation wave could propagate into the unconfined space successfully. In the present study, the process that occurs when a part of the detonation front fails and the failed front reverts to detonation via local explosions is called the reinitiation of the detonation.

Edwards et al. [2], using the soot foil and Schlieren techniques, suggested that the local explosion in reinitiation may occur on the head of the expansion wave generated from the apex of the tube exit. According to their data, the height of the local explosion point from the tube exit is about 10 times the cell width for typical detonation waves. Murray and Lee [3] investigated the position of the local explosion in reinitiation in a circular tube with soot foil. They described the emergence of detonation bubbles on the reinitiation of detonation and showed a quantitative model of diffraction. Lee [4] suggested that the curvature of the wave front and stream tube influence the local explosion of reinitiation.

On the other hand, the detonation wave diffraction may be affected by the deviation angle of the two-dimensional channel. Khasainov et al. [5] investigated the effect of the deviation angle on the reinitiation process by changing the angle of the channel like a fan, from 5° to 90°. When the deviation angle was less than 40°, the local explosion in the reinitiation originated close to the channel wall, but when the deviation angle was greater than 40°, it originated at the flow axis.

Bartlmä and Schröder [6] took high time resolution Schlieren pictures of the detonation diffraction using a multi-spark optical system. While changing the deviation angle from 30° to 150°, they observed the shapes

Correspondence to: kasahara@nuae.nagoya-u.ac.jp

of the diffraction wave propagating in a propane-oxygen mixture every 6 μs and compared the results with the theoretical shape of the diffraction of a shock wave. According to their study, the shapes of the shock wave decoupled from the reaction front showed good agreement with the theoretical shapes of a diffracted shock wave in inert gas, and the decoupled reaction front had little effect on the forward shock wave. However, they only focused on the shape of shock waves decoupled from the reaction front, so they avoided any mention of the shape of a curved detonation wave after reinitiation and local explosion. Pintgen and Shepherd [7] observed diffracted detonations using three visualization methods. They particularly focused on the subcritical (failure of propagation) and critical (limit of propagation) conditions, and showed the development of the shock wave and the reaction front [7-10]. They concluded that the activation energy of a mixture influences the shape of the diffracted wave and its reinitiation. However, their study presented less information regarding the supercritical condition wherein the detonation wave propagates very stably, so our goal was to examine the experimental results in the supercritical condition in a two-dimensional channel using a single mixture.

Arienti and Shepherd [11] conducted a detailed numerical analysis to investigate the effect of activation energy on detonation diffraction, presupposing a single-step reaction in the Arrhenius form. They revealed the dominating factor on the rate of change of the temperature and investigated the abrupt emergence of a transverse detonation wave after the diffraction. However, they made no mention of the cellular structure. In many previous studies, it has been revealed that the reinitiation of detonation is affected by the critical tube diameter, the deviation angle of the channel, and the activation energy. However, there are few studies focused upon the shape of the detonation wave after the local explosion in reinitiation or upon the features of a transverse detonation wave propagating along the shock wave decoupled from a reaction front. Observations of cellular structure with soot foil and Schlieren pictures are mainly used in the experimental study of detonation diffraction. However, the observation of cellular structure with soot foil is an indirect way to understand the detonation front. Although visualization with Schlieren pictures is a direct method, a single-frame picture is commonly used, which is inadequate to track the transformation of the shape of a detonation wave.

We visualized the detonation diffraction with a high-speed video camera by using the two optical techniques of shadowgraph and multi-frame, short-time, open-shutter photography (MSOP) [12]. MSOP is the method that enables us to visualize the wave front and the cellular structure by detecting the detonation self-emission over a relatively long time period. The reinitiation events and propagation of detonation in a bent tube were examined by Nakayama et al. [12] under a variety of conditions. In our previous work [13, 14], using a high-speed video camera made it possible to track the transformation of the wave shape at 2 μs resolution and to observe the reinitiation process, in particular the movement of the transverse detonation wave, directly. However, the dependence on mixture stability was not clearly visualized in our prior studies [13, 14]. In the present experimental study, the positions of the local explosion in reinitiation and the transverse detonation wave were investigated and modeled for five different cases of deviation angles varying from 30° to 150° in a stoichiometric ethylene-oxygen mixture [14] and more stable mixtures (the more stable mixture experiments will be performed by the final manuscript deadline).

2 Experimental setup

The diffraction and reinitiation of two-dimensional detonation waves through a channel of rectangular cross-section were observed. The schematics of the experimental setup and the observation chamber used in the present study are shown in Fig. 1 and Fig. 2, respectively. A diaphragm separated the observation chamber and a dump tank of 0.037 m^3. Both the observation chamber and the dump tank were connected to a rotary pump and a mixing tank. The observation chamber was connected to an igniter circuit, a pulse generator, and a high-speed video camera (Shimadzu HPV-1).

The observation chamber [15] consisted of circular-cross-section tubes, 25.8 mm in diameter, rectangular-cross-section tubes, 20 mm wide by 16 mm deep, and a channel. The gas mixture was supplied from the low-vacuum observation chamber and ignited by a spark plug at the closed end. A Shchelkin spiral at the closed end transferred the deflagration wave to a detonation wave. The detonation wave passing through the channel ruptured the diaphragm, and the high-pressure, high-temperature gas was discharged into the dump tank.

As shown in Fig. 3, we used square channels, 100 mm on a side, with different deflecting angles (θ_d = 30°, 60°, 90°, and 150°). The channel thickness at θ_d = 90° was both 2 mm and 16 mm, while that at the other angles was 16 mm.

A stoichiometric ethylene-oxygen gas mixture was used. The initial pressure of the gas ranged from 20 kPa to 50 kPa by 5 kPa increments at room temperature. Under these conditions, the detonation wave reinitiated in all of the channels.

The shapes of the detonation wave diffraction as the wave passed through the channel were observed using a high-speed video camera. Shadowgraph and MSOP [12] were used as the optical techniques, and the frame interval was set at 2 µs and 4 µs, respectively. The exposure time was 1/4 of the frame interval. The spatial resolution of the images was approximately 0.3 mm in the channel.

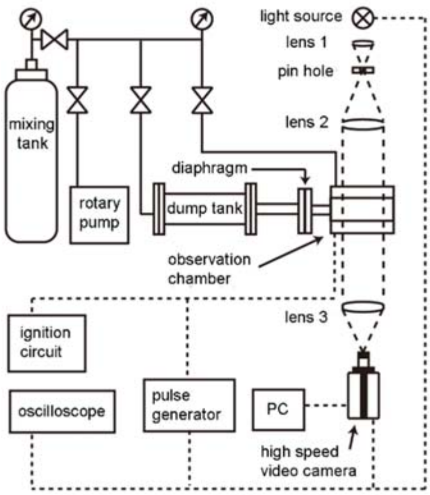

Fig. 1 Schematics of the experimental setup

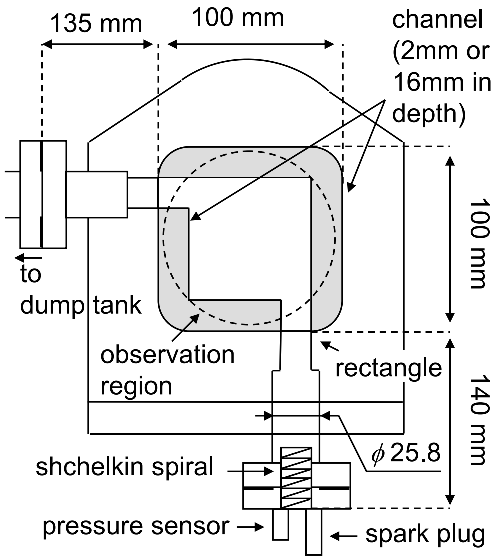

Fig. 2 Side view of the observation chamber

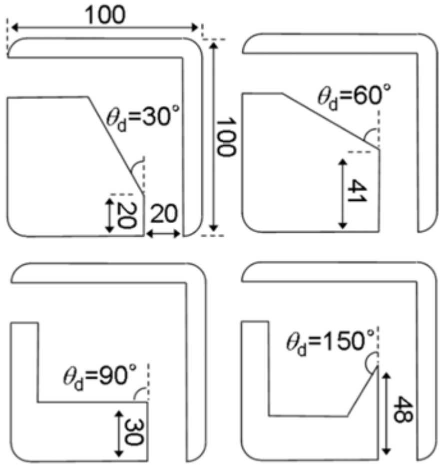

Fig. 3 Schematic diagram of the channel
(channel is 2 mm or 16 mm in depth)

3 Diffracted detonation wave in the thin channel

Figure 4 shows the shadowgraph photographs of detonation diffraction and reinitiation at 6 μs intervals. The gradation in Fig. 4 was inverted, and all of the subsequent shadowgraph pictures were edited similarly. First, a planar detonation wave went into unconfined space from a rectangular tube (see Fig. 4 (a)). A part of the wave was curved and attenuated (see Fig. 4 (b)), and when the shadow of the wave front was not observed in the vicinity of the bottom wall, it indicated that the shock wave was decoupled from the reaction front in this area. It is noteworthy that a black point (recall that the gradation was inverted, so that it was really an emission of white light) emerges abruptly in the upper left corner of Fig. 4 (c). Because this emission is brighter than that from any other wave front, we considered an abrupt exothermic reaction to have occurred at this point. Moreover, in Fig. 4 (d), a clear black point (strong emission) is observed at the left end of the wave, and it approaches the bottom wall, propagating into the shock wave decoupled from the reaction front. This black point at the left end may have been an abrupt exothermic reaction that occurred because the transverse detonation wave interfered with the high-pressure, high-temperature gas induced by the decoupled shock wave. The detonation wave approached and then was reflected from the bottom wall in Fig. 4 (e), and then the entire wave front became the circular detonation wave.

The MSOP photographs of detonation diffraction are shown in Fig. 5. Note that the gradation in Fig. 5 was not inverted. Figure 5 (a) shows a planar detonation wave going into unconfined space. At that time, the cellular structure could be observed as a fine, net-like pattern on the wave front. Figure 5 (b) shows that the wave front was curved near the corner of the channel wall. The net-like pattern was broken near the bottom wall, so the shock wave was decoupled from the reaction front. In Fig. 5 (c), the fan-like locus can be observed in the upper left corner, which corresponds to the position of the black point in Fig. 4 (c). The cellular pattern can be observed on the right side of this fan-like locus, while on the left side, it cannot. In Fig. 5 (d), there is a strong light-emitting line on the wave front, and this line also corresponds to the black point at the left end of the wave in Fig. 4 (d). In Fig. 5 (e), the entire wave front becomes the circular detonation wave.

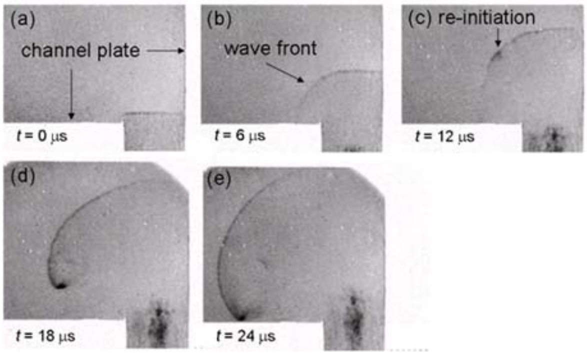

Fig. 4 Continuous pictures of detonation diffraction [14]

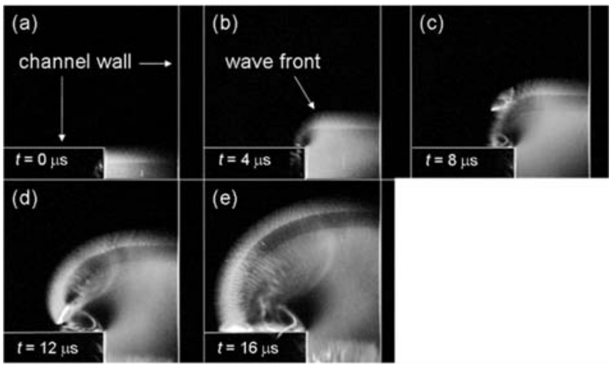

Fig. 5 MSOP of detonation diffraction [14]

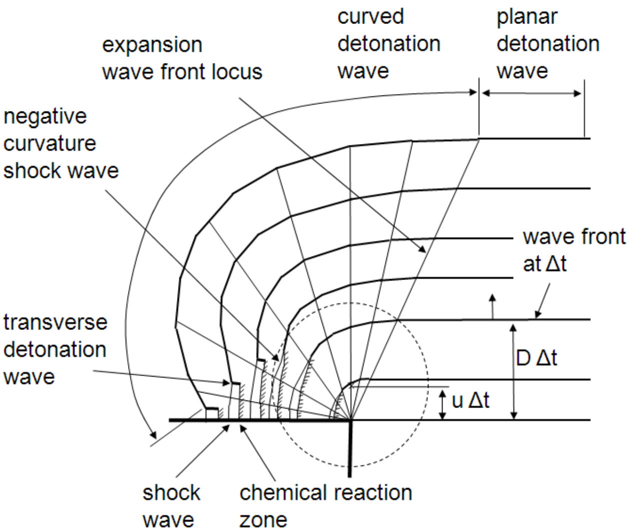

Fig. 6 Schematic picture of detonation diffraction at a rectangular two-dimensional corner (based on present experiments and references of Arienti and Shepherd [11]).

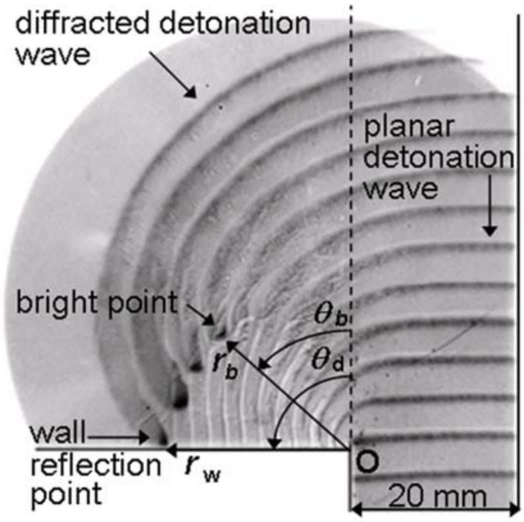

Fig. 7 Definition of the coordinate [14]

References

[1] Zeldovich Ya B, Kogarko SM, Simonov NN. (1956). An Experimental Investigation of Spherical Detonation in Gases. Sov. Tech. Phys. 1: 1689-1713.

[2] Edwards DH, Thomas GO, Nettleton MA. (1979). The Diffraction of a Planar Detonation Wave at an Abrupt Area Change. J. Fluid Mech. 95: 79-96.

[3] Murray SB, Lee JHS. (1983). On the Transformation of Planar Detonation to Cylindrical Detonation. Combust. Flame. 52, 269-289.

[4] Lee JHS. The Detonation Phenomenon, (2008). Cambridge University Press.

[5] Kasainov B, Presles HN, Desbordes D, Demontis P, Vidal P. (2005). Detonation Diffraction from Critical Tubes to Cones. Shock Waves. 14 (3), 187-192.
[6] Bartlmä F, Schröder K. (1986) The Diffraction of a Plane Detonation Wave at a Convex Corner. Combust. Flame. 66, 237-248.
[7] Pintgen F, Shepherd JE. (2009). Detonation Diffraction in Gases. Combust. Flame 156(3), 665-677.
[8] Pintgen F, Shepherd JE. (2007). Stereoscopic Imaging of Transverse Detonations in Diffraction. Journal of Flow Visualization and Imaging Processing. 14, 121-142.
[9] Shepherd JE, Schultz E, Akbar R (2000). Detonation Diffraction. Proceedings of the 22nd International Symposium on Shock Waves 1, 41-48.
[10] Pintgen F. (2004). Detonation Diffraction in Mixtures with Various Degrees of Instability. PhD thesis, California Institute of Technology.
[11] Arienti M, Shepherd JE. (2005). A Numerical Study of Detonation Diffraction. J. Fluid Mech. 529, 117-146.
[12] Nakayama H, Moriya T, Kasahara J, Matsuo A, Sasamoto Y, Funaki I. (2012). Detonation Wave Propagation in Annular Channels with Rectangular Cross-section. Combust. Flame 159, 859-869.
[13] Nagura Y, Kasahara J, Sugiyama Y, Matsuo A. (2013). Comprehensive Visualization of Detonation-Diffraction Structure and Sizes in Unstable and Stable Mixtures, Proceedings of the Combustion Institute 34, 1949-1956.
[14] Nagura Y, Kasahara J, Matsuo A, (2016). Multi-frame visualization for detonation wave diffraction, Shock Waves, 26, 645-656.
[15] Kudo Y, Nagura Y, Kasahara J, Sasamoto Y, Matsuo A. (2011). Oblique Detonation Waves Stabilized in Rectangular-cross-section Bent Tubes. Proceedings of the Combustion Institute 33, 2319-2326.