Diffraction and Re-Initiation of Detonations behind a Backward-facing Step

Shigeharu Ohyagi, Tetsuro Obara Shintaro Hoshi*,
Pin Cai , and Teruo Yoshihashi
Department of Mechanical Engineering, Faculty of Engineering, Saitama University
*** Fluid Industry Co. Ltd.**
255 Shimo-Okubo, Urawa JAPAN 338-8570
e-mail; ooyagi@mech.saitama-u.ac.jp

Abstract

Observations of diffraction phenomena of gaseous detonation waves behind a backward-facing step in a tube are performed by using a high-speed schlieren photography and soot-track record. Mixtures are stoichiometric oxyhydrogen mixtures and those diluted by argon at sub-atmospheric pressures. Three types of phenomena are observed, that is, continuous propagation of detonation, re-initiation after a temporal extinction of detonation and complete extinction of detonation. The re-initiation occurs at a wall surface of the tube behind a reflected shock wave. Positions and conditions of the re-initiation will be discussed.

INTRODUCTION

Diffraction of a shock wave behind a backward-facing step is one of the fundamental topics in the shock wave dynamics and is studied extensively by many researchers. Rarefaction waves emitted from a diffraction corner reduce strength of a incident shock wave. For detonation waves, although the situation is very complex compared with the shock wave, the effects of the rarefaction waves are very important. They decrease temperature of a reaction zone of an incident detonation front so that some parts of the detonation wave will be extinguished. Complex structures of the shock waves and the reaction waves in these processes can be seen in the text book by Soloukhin [1]. The detonation waves, of course, have three-dimensional structures which will play a very important role in this extinguishing process. The well-known “critical diameter” concept by Lee and Matsui[2] had shed a strong light for this diffraction phenomenon. They proposed a criterion that a ratio of a cell width of the mixture to a diameter of the tube is fixed when the steadily propagating detonation wave is emitted into an open space or a tube with a larger diameter. This is a natural conclusion because there are only two parameters with a dimension of length in this phenomenon, that is, the cell width and the diameter. But a detailed phenomenological explanation has not been done yet. Why and how the detonation wave is extinguished remains unsolved.

The present article has been motivated not only by this question but also by researches [3,4] of quasi-detonation waves propagating through an obstacle filled tube. The quasi-detonation wave propagates with velocities smaller than the CJ detonation due to the diffraction and re-initiation. Intervals of the obstacles affect the re-initiation process to modify the propagation of the quasi-detonation. Another situation is propagation in a tube with bend in which the diffraction might cause extinction of flame. In case of the detonation driver of high-performance shock tunnel [5], an initiation of detonation is performed in an initiation tube that is connected with a driver tube at a certain angle. This also might cause extinction or de-coupling of shock and reaction fronts so that a performance of the driver should be affected. Recently, Shepherd [6] has shown fine pictures of detonation waves emerging from a tube into a large volume in critical, sub-critical and supercritical conditions.

With these backgrounds, the present investigation aims at observing the diffraction and the re-initiation process of detonation waves behind a backward-facing step to understand a basic mechanism of these processes.

EXPERIMENTAL

A tube with rectangular cross-section 30x25 mm and length of 3 m is used through which detonation waves propagate. It is divided into a 500 mm driver and a 2500 mm driven section by a Mylar diaphragm. The driver section is filled with a stoichiometric oxyhydrogen mixture at higher initial pressures that is ignited by a spark plug. A detonation wave developed in the driver section through the DDT process breaks the diaphragm and initiates the detonation of the test gas in the driven tube. Relatively, it is easier to establish a steady detonation wave in the test section. In the test section, a metallic plate with thickness of 20 mm is fixed. An upstream end of the plate has a sharp wedge with an apex of 10°. A downstream end forms a backward-facing step through which the detonation wave diffracts so that the height of step is 20 mm. Mixtures are stoichiometric oxyhydrogen mixtures non-diluted (β=[Ar]/[O_2]=0) and diluted with argon (β=4) at pressures p_0=26.7 kPa to 101.3 kPa. Table 1 shows experimental conditions. The phenomena is visualized by high-speed schlieren photographs by using the image converter camera (IMACON 792, Hadland Photonics), a Xe flash lamp with 200μs duration and two concave mirrors with 200 mm in diameter and 2000 mm focal length. A used framing plug-in of the image converter is of 200,000 fps so that a time interval between each frame is 5μs and an exposure time is 1μs. Another visualization by the soot track record has been made to find traces due to the three dimensional structure of the wave front. The sooted plates are installed on the sidewall behind the step. A pressure transducers (PCB 113A24, Piezotronics) embedded on the sidewall can detect pressure variations behind the step.

RESULTS AND DISCUSSIONS

Figure 1 shows typical schlieren photographs. A left series of 6 pictures shows the successive events occurred near the backward facing step, and a right series shows another series of successive events occurred 50 mm away from the step. A condition for these photographs is p_0=53.3kPa, β=0. A diffracted detonation wave decays with a thickening wave front which is de-coupling into a shock front and a deflagration wave behind it at last. These complex wave reflect on the bottom wall of the tube on which a turbulent reacting boundary layer is formed. The last picture on the left series as well as the third picture on the right show the initiation of a cylindrical exploding detonation wave at the foot of the incident shock wave. The detail of this phenomenon cannot be elucidated clearly by these pictures. This re-initiation process is caused by the complex interactions between the shock fronts and the reaction wave. Thus initiated detonation wave propagates cylindrically with a clear three-dimensional structure on the front.

Figure 2 shows a soot track record for the same condition as described above. A fish-scale pattern disappears when the detonation wave enters into the diffracting region. In this region, of course, the detonation wave does not exist. After some distance from the step, a very fine structure appears from the bottom surface of the tube. This region develops like a fan and it covers the whole tube finally. The initial cell size of this exploding detonation is very small because it is an over-driven detonation wave but it increases gradually to the size corresponding to the CJ detonation. The edge of this fan-like region is quite clear. It denotes an intersection between the exploding detonation and the incident shock wave followed by the reaction waves.

Figures 3(a) and 3(b) show pressure histories behind the step. In Fig.3(a), the pressure transducer is embedded on the side wall at a distance D = 0 mm from the step, while in Fig.3(b) it is at a distance D = 65 mm. Abscissas denote pressure divided by the initial pressure (=53.3 kPa) and ordinates denote time elapsed from the time when the wave enter the window. Compared with Fig.1 and Fig.2, the resulted pressure histories can be interpreted as follows: At D = 0 mm, a first small peak is a diffracted incident shock wave which is followed by a reflection from the bottom surface. The third peak is caused by the explosion occurred at the bottom surface when the mixture is re-ignited. The explosion wave travels not only downstream but also upstream. The latter propagates through the burnt gas so that it is decaying blast wave which is called as "retonation". At D = 65 mm for which the position is denoted in Fig.2 and Fig.3, a first wave is the decaying shock wave followed by the reflected shock and the retonation wave. The measuring point lies in the outside of the previous mentioned re-initiated region so that the over-driven detonation front does not detected in this pressure profiles. Because these two schlieren series, soot-track record and two pressure profiles are not taken simultaneously, the relative positions of the pressure transducer are not same strictly. The point where the re-initiation occurs is estimated at the distance 55 mm from the step by the schlieren pictures, while it is estimated at 50 mm by the soot-track. It is possible that the re-initiation point moves several millimeters for each experiment because the three dimensional structure is irregular.

For the mixtures at higher initial pressures as 66.7 kPa, 80.0 kPa and 101 kPa, the detonation waves does not extinguished on the upper surface of the tube. So, in these cases, the detonation waves continue to propagate without interruption. However, even in these cases, there appear a non-fish-scale regions near the step, which shows that the detonation wave extinguishes partly in this region.

For the mixture at 26.7 kPa, no re-initiation is observed so that the detonation wave extinguished completely by the diffraction. But it might be plausible that the flame survives to develop to a detonation wave if the tube were longer enough.

Figure 4 shows the distance from a cell-initiation point and the step. The cell initiation point means the point where the cell structure appears on the bottom surface of the tube. For the pressure lower than 53.3 kPa, it coincides with the re-initiation point mentioned above. For lower initial pressure, reactivity is low and cell sizes are large to make the distance long. Differences between the non-diluted mixtures and the diluted are small because differences between cell sizes are not large, but the re-initiation distances for the diluted mixtures are slightly larger.

SUMMARY

The experimental study on the diffraction process of the detonation wave behind a backward-facing step in a tube has been made. The following conclusions are derived:

(1) When the initial pressure is higher than the critical pressure, the detonation wave travels without interruption but there is a region where the detonation extinguishes behind the step.

(2) When the initial pressure is smaller than the critical pressure, the detonation wave extinguish wholly but it is re-initiated at the bottom surface of the tube where the decoupled shock and reaction fronts reflect. The re-initiated wave is an exploding detona-

tion with a very small cell size.

(3) When the initial pressure decreases further, the re-initiation point moves downstream. At last, the re-initiation does not occur when the pressure is below a certain pressure.

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Table 1 Experimental conditions

Driver gas	$2H_2+O_2$ at 101 kPa and 152 kPa initial pressure
Test gas	$2H_2+O_2+\beta Ar$, β=0,4 at 29.7, 34.7, 53.3, 66.7, 80.0,101kPa
Height of step	20mm

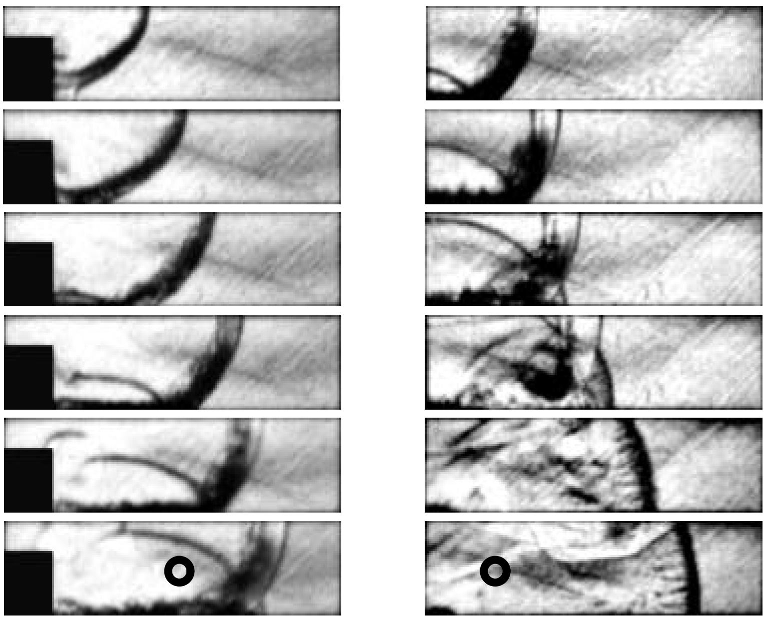

Fig.1 Schlieren photographs for p_0=53.3kPa and β=0. Circles denote the position D=65 mm.

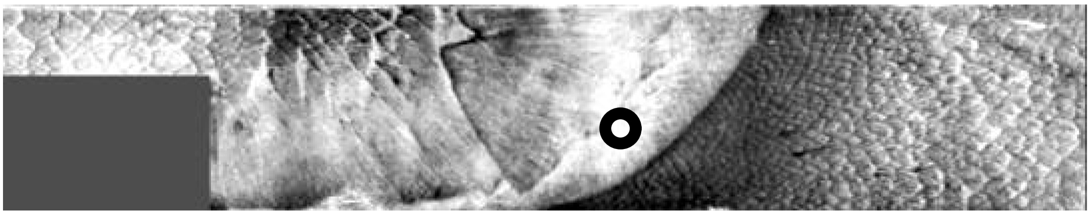

Fig.2 Soot-track record for p_0=53.3kPa and β=0. A circle denotes the position D=65 mm.

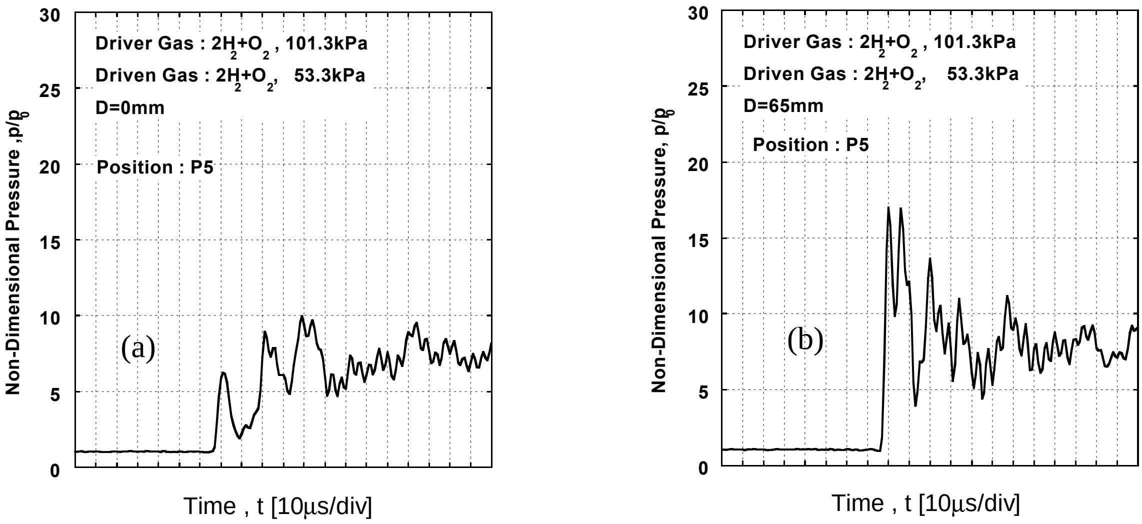

Fig.3 Pressure variation behind the step (a) D=0 mm and (b) D=65 mm for p_0=53.3kPa and β=0.

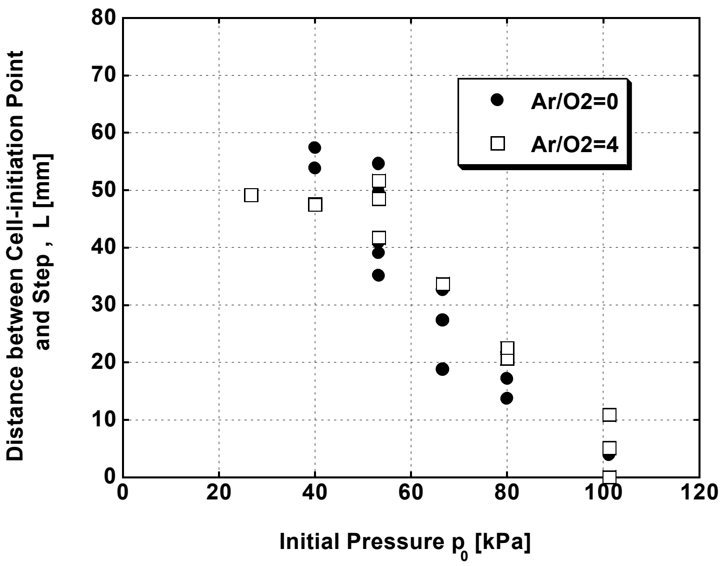

Fig.4 Relation between the re-initiation distance L and the initial pressure of the mixtures.