Effects of opening conditions on the self-ignition of high pressurized hydrogen released through a tube

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1 Introduction

Useful value of high pressure hydrogen is considerable, but there still exists a safety issue due to its possibility of self-ignition. Thus, many studies have been conducting in order to reveal the ignition mechanism and to prevent the phenomenon [1-17]. In present, there seems to be a high probability of diffusion ignition through previous studies [2-17]. Extensive experimental data have been reported in recent years and they are increasing the possibility of diffusion ignition for the self-ignition of high pressure hydrogen. Especially, the visualization images around the tube brought deeper understanding of the mechanism [4-6]. These results showed a general tendency that the possibility of self-ignition can increase as a burst pressure is high, a diameter and length of the tube is small and long. Besides, several numerical simulations have also conducted to aid limitative experimental data [10-15]. The numerical visualization brought an intuitive grasp on the phenomenon [11-12] because it is difficult to obtain experimental images that can show the whole process of a flow development.

From gathering previous results, the ignition mechanism and essentials to initiate the ignition are quite clear as followings. First, a high burst pressure is necessary so that an air can be heated enough. Second, a sufficient tube length that a mixing region induced by flow interactions can be developed is needed. Despite of these observations, understanding of the phenomenon is still remained imperfect because a flow development with failure conditions of a rupture disk is not known. In fact, the ignition characteristics are not always the same, even though main burst conditions such as a burst pressure and extension tube are the same. This is because an initial flow can be different as an open condition is varied, which can result in a different ignition feature. For example, in some cases, a rupture disk cannot open fully and a border of a disk can be remained after a burst, which can lead asymmetric flow or smaller open area of rupture disk. Therefore, it is necessary to observe the bursting instant and to observe any effect of open condition of a disk on the self-ignition.

This study has two aims in this respect. One is to investigate an initial flow immediately after failure of rupture disk and its effect on the self-ignition as observing visualization images for the whole tube. The other is to investigate the different ignition patterns with various open area of a disk. Experimental study was conducted to achieve these goals using a rupture disk and a rectangular extension tube. And a plate that has a hole of different diameter was applied behind of a disk to change an open area. In this paper, the effect of initial flow development on the self-ignition was described using visualization images of the whole tube and pressure data. Additionally, the effect of open area of the disk on the self- ignition inside the tube was analyzed together.

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2 Experimental Setup

A schematic of the experimental apparatus is shown in Fig. 1. It consists of a hydrogen cylinder, a storage tank, a rupture disk and an extension tube. Mylar polyester film of various thicknesses was used to control the burst pressure as a rupture disk. A piezoresistive pressure transducer (Kulite, ETM-HT-375) was installed on the storage tank wall to measure a burst pressure. The extension tube has 11 mm by 11 mm square shaped cross-section and its length is 200 mm. Window glass substitute for both side walls to obtain visualization images. Open area of a disk is basically same as the cross-sectional area of the extension tube, but it can be varied by placing a plate with a smaller hole behind of a disk. The several plates that the area ratio of the hole to the tube cross-section is 0.25~0.75 were applied to change open area. The detailed view on the test model including the plates is shown in Fig. 2

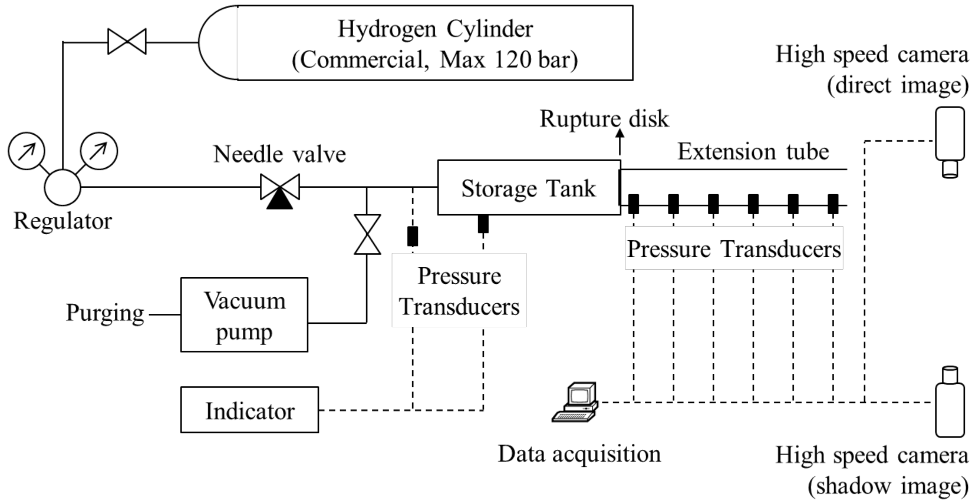


Fig. 1 Schematic of experimental configuration

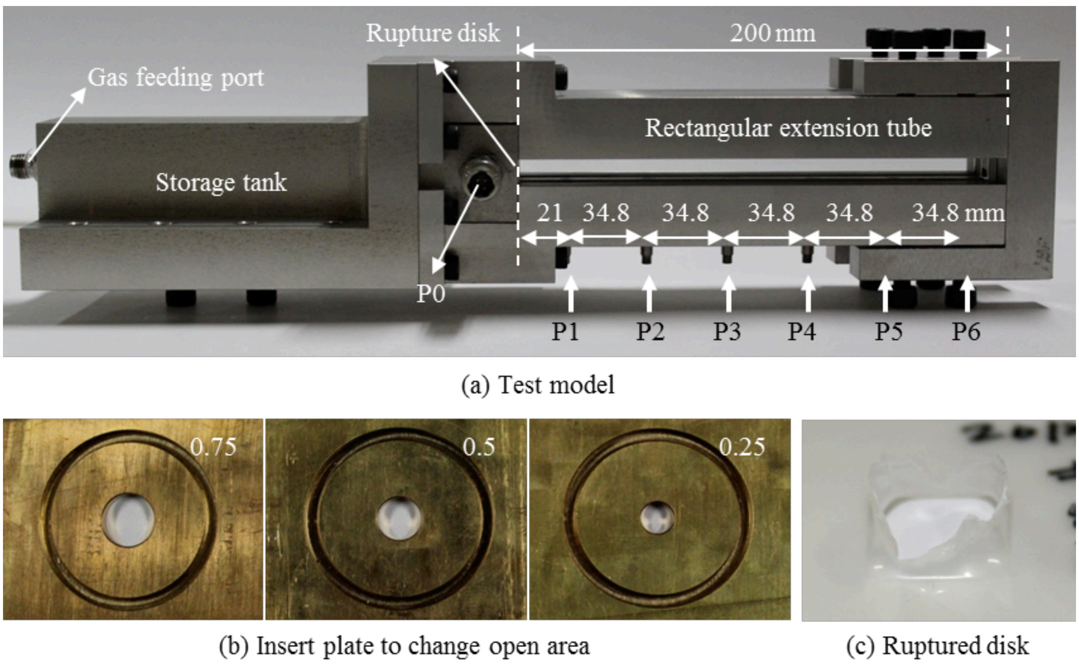


Fig. 2 Components of a test model and assembly

Pressure measurements and flow visualizations were obtained as experimental data and all measurement systems were synchronized by a triggering signal. Six piezoelectric pressure transducers (PCB Piezotronics, 113A26) were installed to measure the pressure on the wall surface. First pressure transducer located 21 mm from a rupture disk was used as a triggering source to excite other devices. Next transducers are installed every 34.8 mm. Shadowgraph and direct images were simultaneously obtained at the intervals of 5 µs and 10 µs using two high-speed cameras (Phantom v710). Exposure time of images was set by 2 µs and 9.6 µs, respectively.

3 An example of simple equation

The experimental conditions and their results are shown in Fig. 3. Solid symbols present the case of self-ignition and open symbols stand for the no ignition. In this study, a burst pressure was limited below 110 bar because the window glass can break easily above 100 bar. Although a burst pressure is limited, however the results show the clear tendency for the self-ignition with open area ratio. Basically, the self- ignition can be initiated at the burst pressure of above 85 bar for the open area ratio of one. This result is similar with that of Kim et al which has similar size of the extension tube [6]. The minimum burst pressure that can initiate the self-ignition increases slightly as the open area ratio decreases, but this tendency is preserved well until the open area ratio decreases by 0.5. For example, in case that open area ratio is 0.5, the self-ignition was initiated at the burst pressure of 88.9 bar, but ignition was failed at 87.8 bar. This tendency is not preserved any more when the open area ratio is smaller than 0.5. The ignition was failed at open area ratio of below 0.5 although a burst pressure is high enough. Any ignition was not initiated at open area ratio of 0.25, even though the burst pressure was nearly 100 bar. This result suggests that there can be any critical open area ratio to prevent an ignition at given downstream conditions.

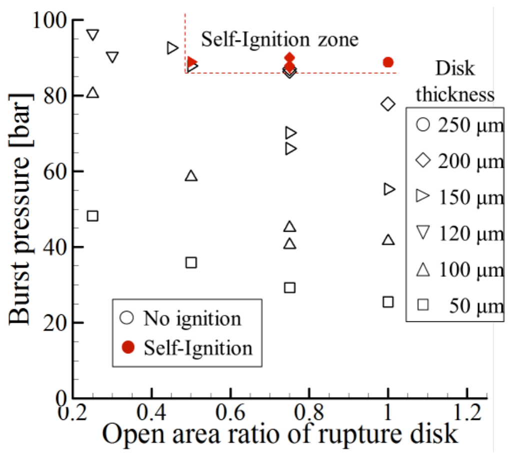


Fig. 3 Initiation tendency of Self-ignition with open area ratio

Figure 4 shows the shadowgraph and direct images for the self-ignition and flame propagation at the burst pressure of 91 bar. The overall process of self-ignition and flame propagation is as follows. An initial flat disk is spherically expanded gradually as a pressure of storage tank increases, and then exploded from the center of the disk. After that, hydrogen gas discharges abruptly and very small spherical shock is generated through partially opened area in 5 µs. The generated shock is propagated to the wall as forming a thin mixing region that a density gradient exists in 10 µs. The shock arrived at the wall is reflected to the center again and spherical shock becomes flatter and closer to plane waves in 20 µs. Simultaneously, small and weak flame is observed near the disk in direct images. This weak flame is preserved near the same location until 50 µs, and after that disappeared. Whereas, incident shock is propagated downstream gradually and ignition near the boundary layer is initiated at 50 µs.

After that the flame is developed to center region gradually. The visualization images show that the ignition is always initiated near the boundary layer first and it is expanded to the center of tube.

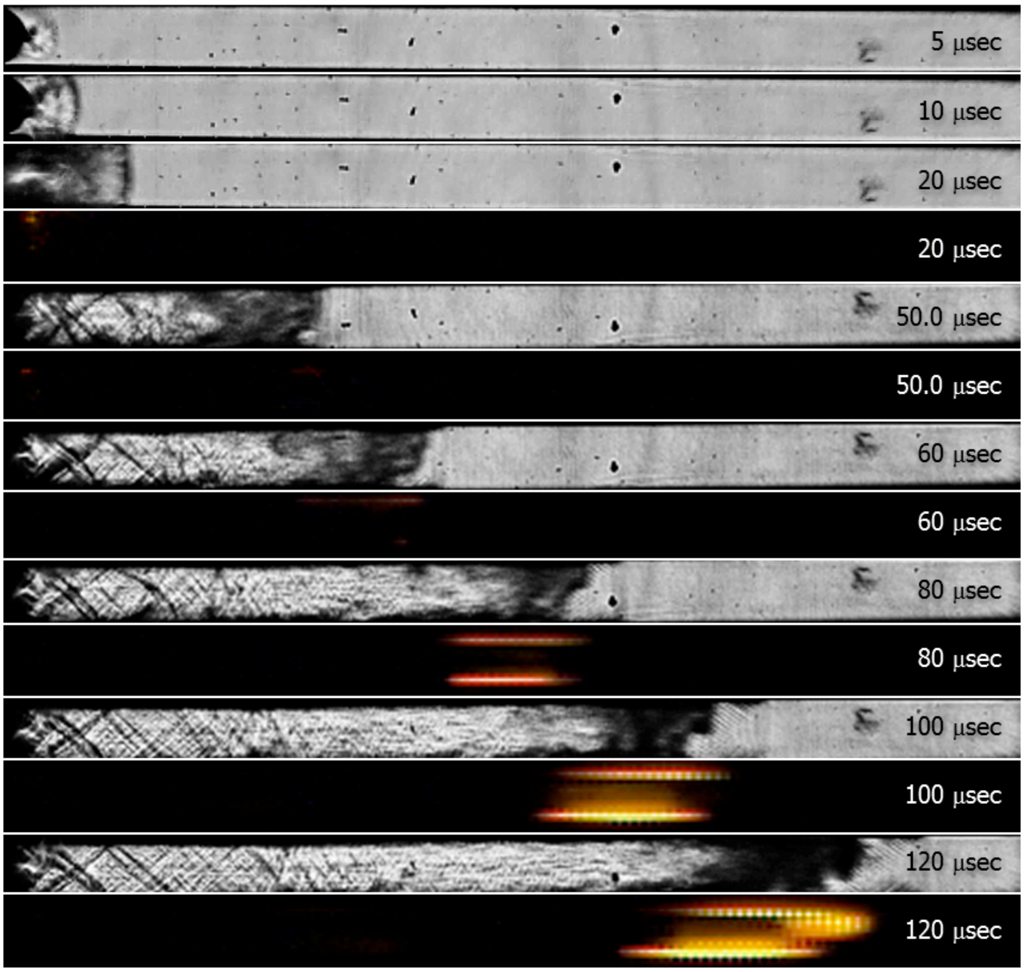
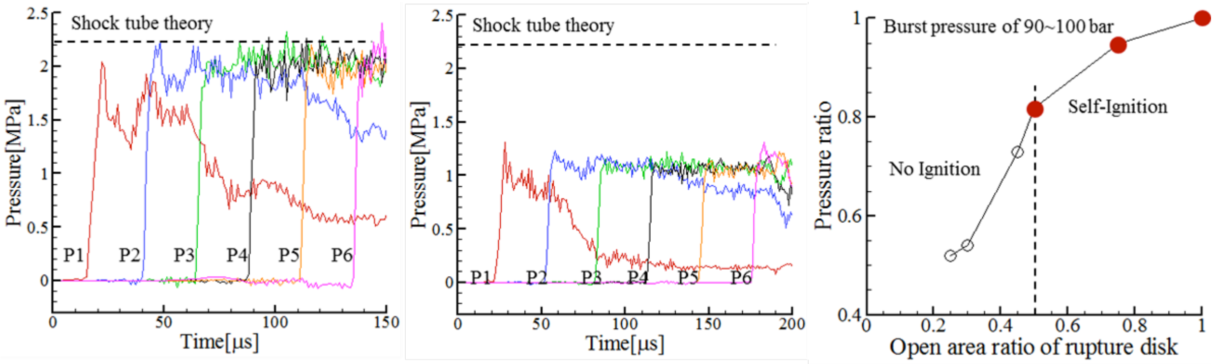


Fig. 4 Visualization image at burst pressure of 90 bar (open area ratio of 1.0)

When the burst pressure is higher, the overall process is very similar, but a flame near the disk is generated more strongly so that the Mylar disk can be burned. However, although the initial ignition and flame near the disk is generated strongly and fast, this is not affected next self-ignition mechanism. This phenomenon which an ignition is generated near the disk is observed when a burst pressure is higher than 80 bar regardless of the self-ignition process inside the tube. This is because the generated shock has sufficient strength at the rupturing moment and it can heat up around air locally although the region is very small. Therefore, the similar phenomenon is observed at the condition of smaller open area ratio and it cannot affect the main ignition process. However, the ignition near the disk is not observed at sufficiently high burst pressure when the disk is ruptured at the condition that the open area is lower than 0.5.

Figure 5 shows the pressure trace with open area ratio. (a) and (b) of the figure are the pressure at the same burst pressure of 90 bar. The one is the case of self-ignition and the other is non-ignition. As shown in results, the generated pressure on the surface is small when open area ratio decreases. This means that the generated shock is weak at a small open area although the burst pressure is the same, which causes that the air cannot be heated enough and ignition also cannot be initiated. The pressure ratio of measurements to the shock tube theory is presented with open area ratio in (c). The pressure ratio decreases to 0.8 gradually until open area ratio is reduced by 0.5, but self-ignition is observed.

When the open area ratio is further reduced the pressure ratio decreases suddenly and the ignition is not initiated. From the measured pressure for each open area ratio, the burst pressure can be converted to that of shock tube theory. For example, the burst pressure that corresponds to shock tube theory is 61 bar and the tube diameter corresponds to 8 mm when open area ratio is 0.5. According to previous results [4], the minimum burst pressure of the self-ignition is 65 bar when the tube diameter is 10 mm. Considering different burst conditions, it seems that the minimum burst pressure that can initiate the self-ignition is very similar.



(a) Open area ratio: 0.75 (b) Open area ratio: 0.3 (c) Pressure ratio with open area ratio

Fig. 5 Pressure traces with open area ratio

4 Conclusions

Self-ignition characteristics were investigated when high pressure hydrogen was released suddenly through a tube into the air by the failure of a rupture disk. The characteristics were analyzed using the visualization images for the whole tube from the rupturing instant of the disk and the pressure data on the wall surface.

The visualization images showed that the initial ignition region that has not been observed in the previous results exists near the disk. In this study, the small spherical shock generated immediately after bursting is changed to planar in about 20 μs and the ignition is initiated in this stage and then preserved for about 20~30 μs. However, this initial ignition cannot affect the whole process of the self-ignition as it is not propagated downstream and disappeared. After that, as already known ignition mechanism, another ignition region near the boundary layer is formed and then expands to the center. The experimental images showed that the ignition is always started from the boundary layer and this is the most important things for the self-ignition.

The experimental data showed another result that the self-ignition cannot be initiated when an open area of a disk is reduced sufficiently although a burst pressure is high enough to initiate the self-ignition. The pressure decreases suddenly when open area ratio decreases below 0.5 and the ignition is failed. This is analyzed because the shock generated by a burst of disk becomes weak as an open area decreases and the air cannot be heated sufficiently. The results suggest that the unwanted ignition can be avoided as applying a kind of border in a rupture disk when a rupture disk is using for a safety purpose.

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