Effects of open area of a rupture disk on the self-ignition of high pressurized hydrogen released through a tube

Hyoung Jin Lee[1], Sang Yoon Lee[2], Bok Jik Lee[3] and In-Seuck Jeung[2]
[1]LIG Nex1. Co., Ltd.
Gyeonggi, Republic of Korea
[2]Department of Mechanical and Aerospace Engineering, Seoul National University
Seoul, Republic of Korea
[3]School of Mechanical Engineering, Gwangju Institute of Science and Technology
Gwangju, Republic of Korea

1 Introduction

Utility 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 conducted in order to reveal the ignition mechanism and to prevent the phenomenon. In present, there seems to be a high probability of diffusion ignition through previous studies [1-11]. 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 [3-4]. 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 been conducted to aid limitative experimental data [5-9]. The numerical visualization brought an intuitive grasp on the phenomenon [6-7].

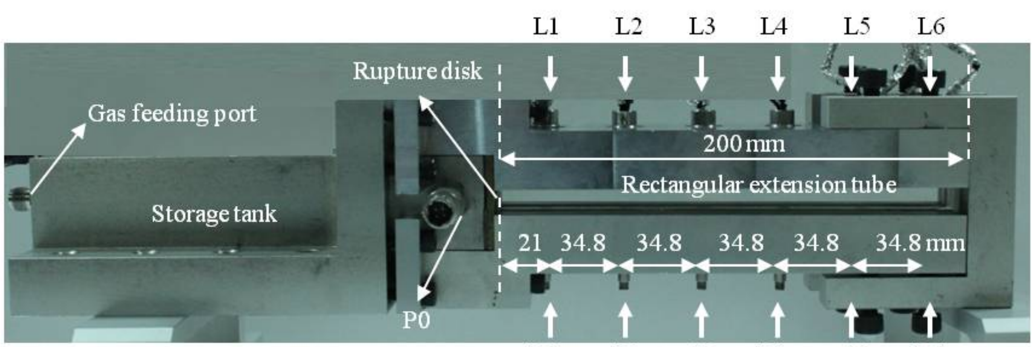
From previous results, the ignition mechanism and essentials to initiate the ignition are quite clear as followings. First, a high burst pressure is necessary so that an air can be heated enough. Second, a sufficient tube length that a mixing region induced by flow interactions can be developed is needed. Despite of these observations, understanding of the phenomenon has 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. Regarding to this, numerical study showed different ignition feature with burst conditions [11], but it has not been reported through experimental studies yet.

Correspondence to: enjis@snu.ac.kr

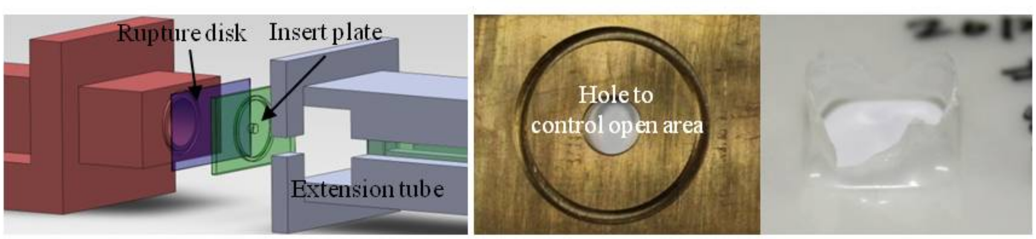
This study has two aims in this respect. One is to investigate an initial flow immediately after failure of a rupture disk and its effect on the self-ignition as observing visualization images for the whole tube. The other is to investigate the different ignition patterns with various open area of a disk. Different open area ratio can simulate the different border of a disk after a failure. Experimental study was conducted to achieve these goals using a rupture disk and a rectangular extension tube. 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.

2 Experimental Setup

Experimental apparatus consists of a hydrogen booster, 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 pressure was measured 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 0.125~0.75 were applied to change open area. The detailed view on the test model including the plates is shown in Fig. 1. Pressure and light measurements and flow visualizations were obtained as experimental data and all measurement systems were synchronized by a triggering signal. Six piezoelectric pressure transducers and photodiodes were installed to measure the pressure on the upper and lower surface of test model. 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 using two high-speed cameras.



(a) Test model



(b) Schematic of disk and insert plate (c) Insert plate (d) Ruptured disk

Fig. 1 Components of a test model and assembly

3 Results and Discussion

Figure 2 shows the shadowgraph images for the self-ignition at the burst pressure of 9.4 MPa. 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 ruptured. After that, hydrogen gas discharges abruptly and very small spherical shock is generated through partially opened area in ~3 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 wave in ~20 μs. Simultaneously, a small and weak flame is observed near the disk in direct images. This weak flame is preserved at the same location for a moment, and after that disappeared. Whereas, incident shock is propagated downstream gradually and ignition near the boundary layer is initiated at ~40 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.

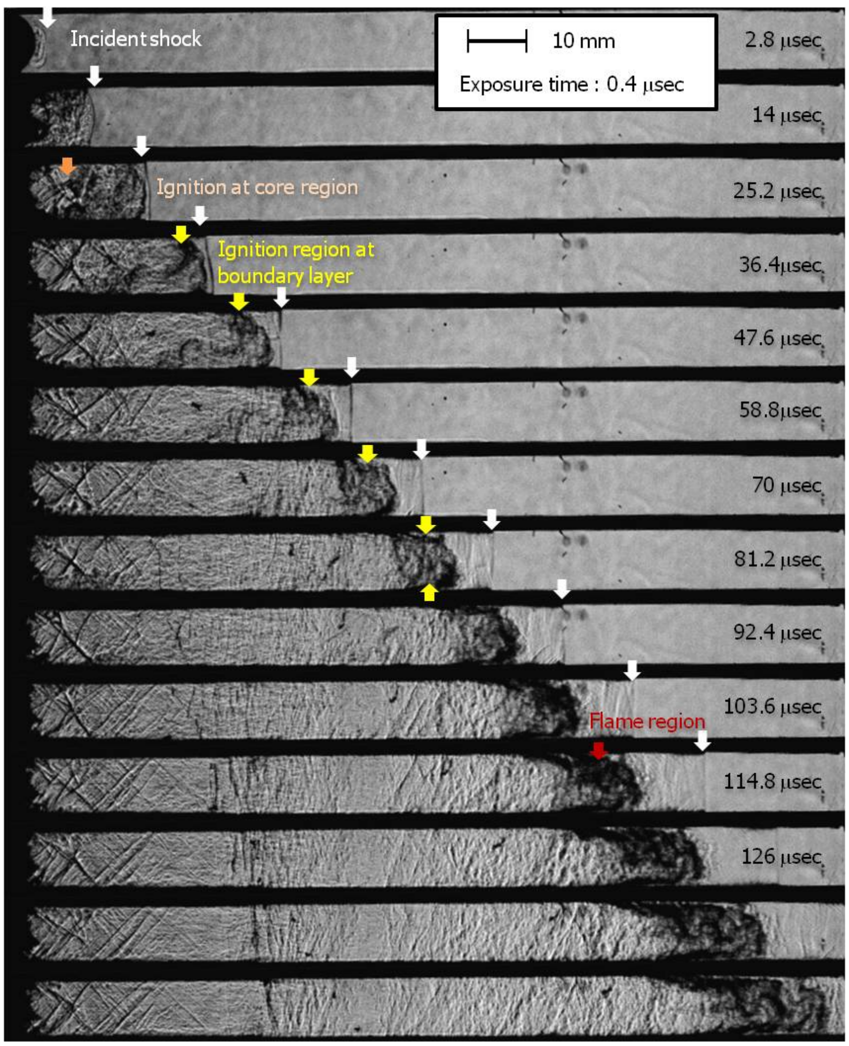


Fig. 2 Visualization image at burst pressure of 9.4 MPa (open area ratio of 1.0)

Figure 3 shows the direct images at the burst pressure of 11 MPa. The overall process is very similar with the case of 9.4 MPa, 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 does not affect next self-ignition mechanism. This phenomenon which an ignition is generated near the disk is observed when a burst pressure is higher than 8 MPa. And that is corresponded to the minimum burst pressure and this means that heating condition is satisfied. Furthermore, a strong mixing region developed by complex flow interaction is observed immediately after a failure from a visualization image. Thus, the generation of initial ignition is presumed that the induction time is very short because equivalence ratio of mixture become to one in a moment after a failure, as the condition that heating by shock is sufficient.

Fig. 3 Direct image at burst pressure of 11 MPa (open area ratio of 1.0)

Figure 4 is another visualization images observed local ignition, which is observed in some cases randomly and this is a similar phenomenon with the initial ignition. Local ignition is also initiated from a strong mixing region, which is induced by complex flow interactions at a local point. After that, it is propagated shortly, then disappeared soon or merged to the ignition region initiated near the boundary layer. Consequently, it seems that local ignition is also generated from the same reasons with the initial ignition, which is initiated suddenly by short induction time induced by a strong mixing. Figure 5 shows the local maximum pressure value with open area ratio and burst pressure. Red and solid symbolic line represents the case of self-ignition, and dashed and open symbolic line corresponds to the non-ignition. Difference of the pressure value is quite large with the self and non ignition conditions at the open area ratio of 0.5 and 0.25. And pressure increase is shown between position 2 and 3 and shock speed is also increase. This is because the planar shock is formed completely and this was confirmed from the visualization images. Therefore, downstream of position 2 has the mixing and heating conditions that self-ignition can be initiated. However, this tendency is not preserved at the open area ratio of 0.125. As shown in Fig. 5(c), the difference of pressure value is not large between the case of self and non ignition. The reason is not clear because of the lack of visualization images, but it is possible that the local ignition as shown in Fig. 5 might be propagated.

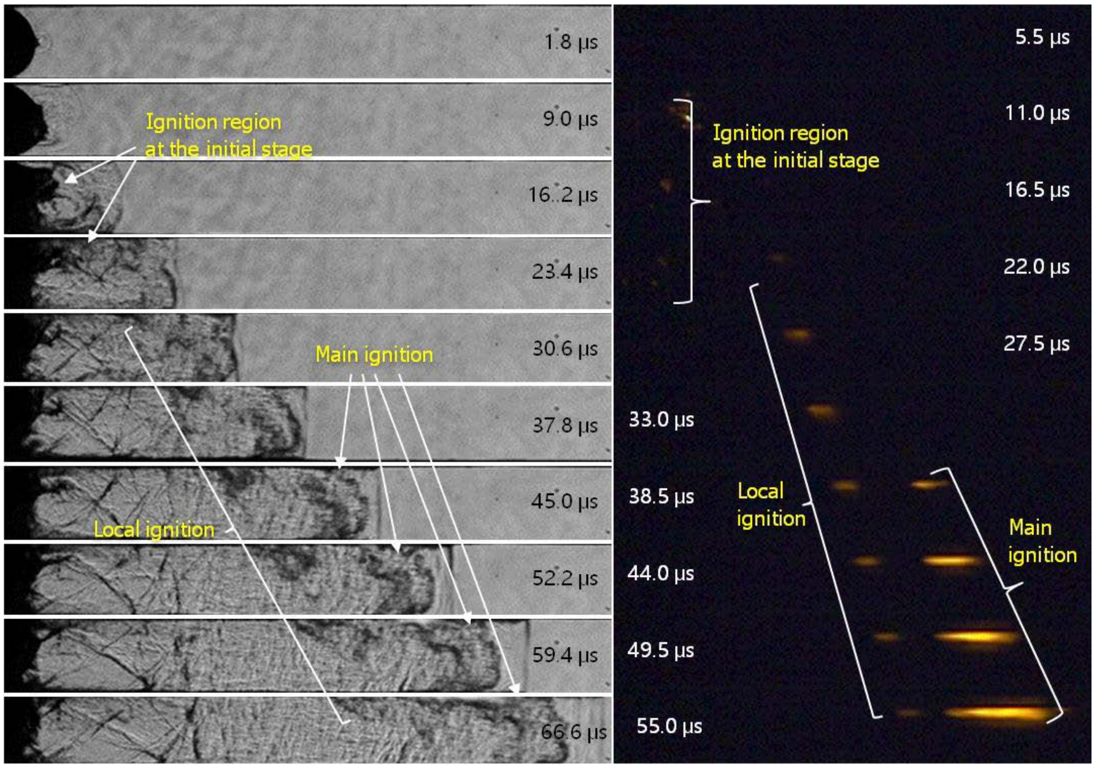


Fig. 4 Visualization image at burst pressure of 8.6 MPa (open area ratio of 1.0)

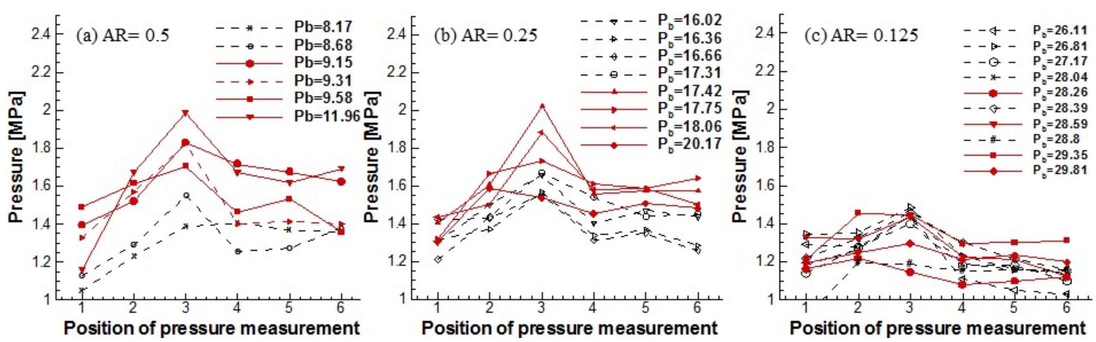


Fig. 5 Maximum pressure traces with downstream position

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 and light signals 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. However, this initial ignition cannot affect the whole process of the self-ignition as it is not propagated downstream and disappeared when the burst pressure is about 10 MPa. 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 thing for the self-ignition.

The experimental data showed another result that the self-ignition is not obtained easily when the open area ratio is reduced sufficiently. The results suggest that the unwanted ignition can be avoided as applying a kind of border in the rupture disk when a rupture disk is using for a safety purpose. But it is possible that the self-ignition can be initiated when the burst pressure is high enough at small open area. When the area ratio is higher than 0.25 it seems that the mechanism of self-ignition initiated from the heating and mixing induced by the shock and flow interactions is preserved from the pressure data inside the tube. However, at open area ratio of 0.125, it is difficult to classify the limit of burst pressure that the self-ignition can be initiated and it seems that the mechanism might be different. The reason is unclear, but it is plausible that the self-ignition can be induced from the local ignition.

References

[1] Wolanski P, Wojcicki S. (1973). Investigation into mechanism of the diffusion ignition of a combustible gas flowing into oxidizing atmosphere. Proc. Combust. Inst. 14: 1217.

[2] Dryer FL, Chaos M, Zhao Z, Stein JN, Alpert JY, Homer CJ. (2007). Spontaneous ignition of pressurized releases of hydrogen and natural gas into air. Combust. Sci. Tech. 179: 663.

[3] Mogi T, Wada Y, Ogata Y, Hayashi AK. (2009). Self-ignition and flame propagation of high- pressure hydrogen jet during sudden discharge from a pipe. Int. J. Hydrogen Energy 34: 5810.

[4] Kim YR, Lee HJ, Kim SH, Jeung IS. (2013). A flow visualization study on self-ignition of high pressure hydrogen gas released into a tube. Proc. Combust. Inst. 34: 2057.

[5] Xu BP, El H, Wen JX, Dembele S, Tam VHY, Donchev T. (2008). Numerical study on the spontaneous ignition of pressurised hydrogen release through a tube into air J. Loss Prevent Proc. 21: 205

[6] Wen JX, Xu BP, Tam VHY. (2009). Numerical study on spontaneous ignition of pressurized hydrogen release through a length of tube. Combust. Flame 156: 2173

[7] Lee BJ, Jeung IS. (2009). Numerical study of spontaneous ignition of pressurized hydrogen released by the failure of a rupture disk into a tube. Int. J. Hydrogen Energy. 34: 8763.

[8] Bragin MV, Molkov VV. (2011). Physics of spontaneous ignition of high-pressure hydrogen release and transition to jet fire. Int. J. Hydrogen Energy 36: 2589

[9] Yamada E, Kitabayashi N, Hayashi AK, Tsuboi N. (2011). Mechanism of high pressure hydrogen auto-ignition when spouting into air. Int. J. Hydrogen Energy 36: 2560

[10] Golovastov S, Bocharnikov V. (2012). The influence of diaphragm rupture rate on spontaneous self-ignition of pressurized hydrogen. Int. J. Hydrogen Energy 37: 10956

[11] Lee HJ, Park JH, Kim SD, Kim SH, Jeung IS. Numerical study on the spontaneous-ignition features of high-pressure hydrogen released through a tube with burst conditions. (2015). Proc. Combust. Inst. 35: 2173.