Letter

414

Detonation of LOX/LNG mixture induced by their vapor cloud deflagration

Dongjoon Kim*†, Yozo Kakudate**, and Shu Usuba**

*Kyungil University, 50 Gamasilgil, Hyangup, Gyeongsan, Gyeongbuk 712−701, KOREA
Phone +82−53−600−5411
†Corresponding author : blastwaves@hotmail.com

**National Institute of Advanced Industrial Science and Technology (AIST),
Tsukuba Central 5, 1−1−1, Higashi, Tsukuba, Ibaraki 305−8565, JAPAN

Received : June 8, 2016 Accepted : November 2, 2016

Abstract

As part of the safety evaluation for launching a rocket using LOX and LNG, we investigated whether a vapor cloud explosion induces the explosion of the LOX/LNG mixture. The experiments were conducted by varying the vertical distance between the LOX/LNG mixture and the vapor cloud. The results show that when the distance is sufficiently small, the explosion of the LOX/LNG mixture is induced. The shock wave generated from the induced explosion shows that a considerable amount of the LOX/LNG mixture explodes. Furthermore, the stainless steel pan for the LOX/LNG mixture fragmented into small pieces. All results demonstrated that induced explosion is detonation.

Keywords : LOX, LNG, induced explosion, vapor cloud, detonation

1. Introduction

The Japan Aerospace Exploration Agency (JAXA) has been conducting a safety evaluation of a rocket using liquid oxygen (LOX) and liquefied natural gas (LNG)[1]. When the rocket is preparing for launch, it has high risk for accident explosion. One of possible accident scenarios is that the rocket falls off of the launch pad before it is launched, causing the LOX and LNG to leak from the tanks and form a pool of liquid mixture (LOX/LNG mixture) on the ground surface. It should be noted that LOX and LNG can coexist in a liquid phase, and previous studies show that the LOX/LNG mixture is a detonable material[2]. This is the main reason why this study is required, even though there are a lot of studies for the safety evaluation of H-II rocket. Liquid hydrogen and LOX cannot coexist in a liquid phase.

At the same time, the combustible vapor cloud is easily formed by the evaporation of LOX and LNG. It is well known that the methane/oxygen gas mixture has a very low minimum ignition energy[3]. Therefore, the formation of the LOX/LNG mixture indicates a high potential for an induced explosion by the explosion of the vapor cloud.

Unfortunately, however, the ignition conditions for the explosion of the LOX/LNG mixture are not very well known. For the first step of the safety evaluation, this study investigated whether the deflagration of the methane/oxygen gas mixture induces the explosion of the LOX/LNG mixture.

2. Experiment

The explosion experiment was conducted in an oval-shaped (or egg-shaped) chamber with vertical and horizontal diameters of 6.0 and 3.9 m, respectively. Figure 1 shows the experimental setup. To form the LOX/LNG mixture, a stainless steel cake-shaped pan was fixed over the expanded metal which a steel plate was squeezed on two sides. The pan was located at the center of the chamber. The diameter, height, and wall thickness of the pan are 400, 20, and 1 mm, respectively. After the LOX and LNG were set in separate Dewar vessels, they were poured into the pan via remote control to form the LOX/LNG mixture for the sake of safety. To yield 1 kg of the stoichiometric composition in the pan, the initial masses of the LOX and LNG in each Dewar vessel were decided through prior investigation that measured the weight of the pan with the time after they had poured into the pan.

When the LOX/LNG mixture was exploded, the depth was approximately 10 mm.

In this experiment, the LOX/LNG mixture was ignited by the explosion of a premixed gas mixture. For the gas explosion, the methane/oxygen gas mixture of the stoichiometric composition was injected into a spherical rubber balloon above the LOX/LNG mixture. The gas mixture in the balloon was ignited at the center by a fused Nichrome wire, as previous study was conducted[4]. The diameter of the balloon and the mass of gas mixture are approximately 100 mm and 2 g.

For conducting reproducible experiments, the vapor cloud, which is formed by the evaporated from the LOX/LNG mixture, was removed by an exhaust port which was located below the pan. It should be noted that the vapor that was just evaporated from the LOX/LNG mixture is heavier than air because the density of low-temperature vapor is larger than that of room-temperature air.

To investigate whether the gas explosion induces the explosion of the LOX/LNG mixture, the distances (H) from the center of the balloon to the pan bottom were varied. To confirm the induced explosion and estimate the explosion strength, the blast wave pressures were measured. The ignition and the measurement methods were conducted as in a previous study[4].

3. Results and discussion

The experimental conditions and results are summarized in Table 1. Figure 2 (A) shows the time histories of the blast wave pressures of Exps. 1 and 2. In the figure, in order to compare easily two histories, the time is shifted so that the two times of arrival (TOAs) are the same. When the blast wave arrives, the pressures increase continuously, as in a typical gas deflagration. The history of Exp. 1 without the LOX/LNG mixture is almost identical to that of Exp. 2 with the LOX/LNG mixture. It is concluded that the gas explosion in Exp. 2 did not induce the explosion of the LOX/LNG mixture.

However, the history of Exp. 3 was completely different from that of Exp. 2. Figure 2(B) shows that the peak overpressure of Exp. 3 is several hundred times larger than that of Exp. 2. It is concluded that the gas explosion induced the LOX/LNG explosion. In order to estimate the exploded mass of the LOX/LNG mixture roughly, TNT equivalent weights (M_{eq}) were calculated by comparing with the Baker's TNT data[5] after the impulse and the distance were scaled by the mass of the LOX/LNG mixture. Each M_{eq} of Exp. 3 for the peak overpressure and the impulse were estimated 1.5 kg and 0.9 kg. However, it should be mentioned that there are some errors for the values of M_{eq} because the explosion energies of the LOX/LNG mixture and TNT are not the same. In addition, the Baker's TNT data suppose the point explosion. Even though the accuracy estimation for M_{eq} is difficult, it is considered that considerable amount of the LOX/LNG mixture was exploded.

Table 1 Experimental conditions and results of LOX/LNG explosion for different H values.

Exp.	Mass (g) Gas	Mass (g) LOX/LNG	Distance H (mm)	LOX/LNG explosion
1	2.00	0	620	–
2	1.98	~1000	620	No
3	1.98	~1000	210	Yes

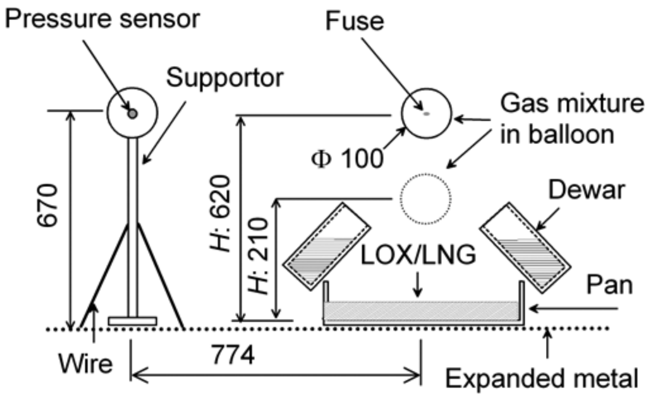

Figure 1 Experimental setup

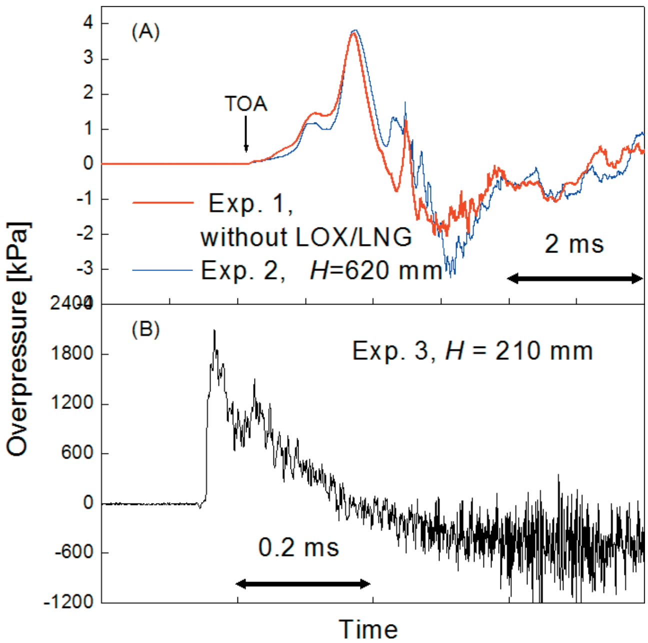

Figure 2 Time histories of blast wave pressures of Exps. 1 and 2 (A) and Exp. 3 (B)

Furthermore, Figure 2 (B) also shows that the pressure increased discontinuously, which is a shock wave. It is well known that the formation of a shock wave is deeply connected with the volume variation velocity ($V_{vol.}$) of burnt gas generated by the combustion[6)−8)]. It is considered that $V_{vol.}$ of Exp. 3 was dramatically faster than $V_{vol.}$ of Exp. 2. Even though $V_{vol.}$ was not measured in this experiment, it is considered that the detonation occurred.

Not only shock waves but also fragments demonstrate that the detonation of the LOX/LNG mixture occurred. Figure 3 shows the 1-mm-thick stainless steel pan. After the explosion, most of the fragments that were remained in chamber were collected. It is confirmed that the pan was destroyed completely and fragmented into small pieces of a couple of tens millimeters in size. We confirmed the reproducibility of the results by performing multiple

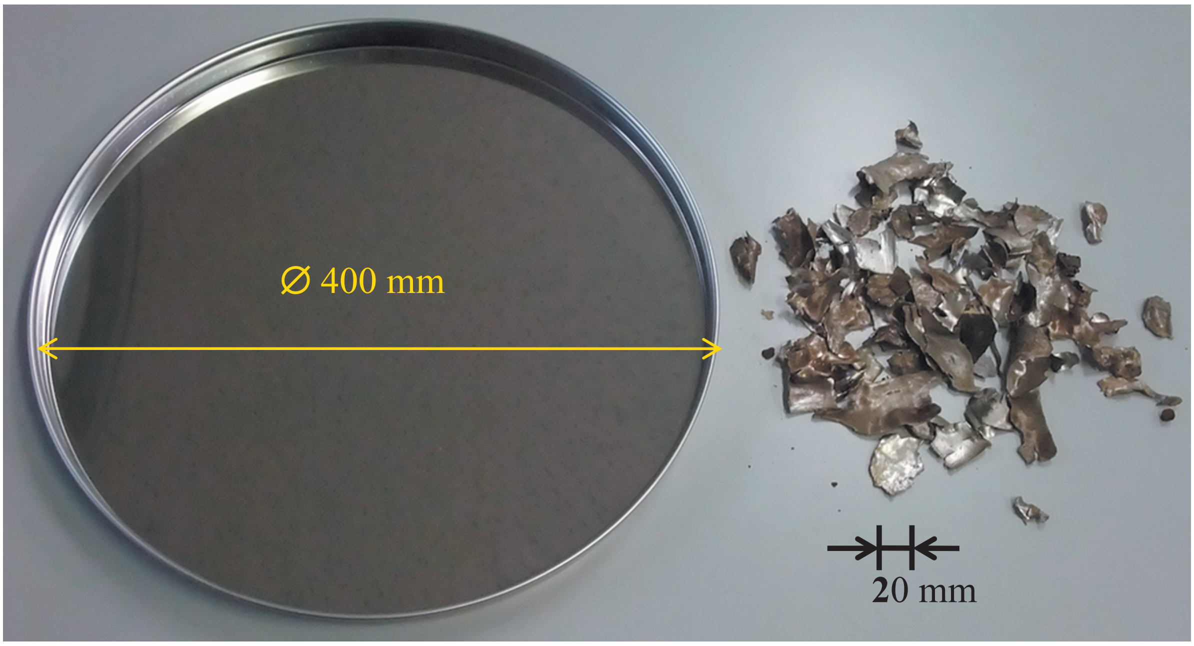

Figure 3 Stainless steel pan before and after explosion in Exp. 3

experiments. Furthermore, we also confirmed that some pan fragments were melted and made craters on the steel walls of the chamber. All results indicate that the LOX/LNG mixture burns violently, which suggests the occurrence of the detonation of the LOX/LNG mixture.

4. Conclusions

This study investigated whether the gas explosion induces the explosion of the LOX/LNG mixture. The results show that when the distance from the gas explosion to the LOX/LNG mixture is short enough, the explosion of the LOX/LNG mixture is induced. The blast wave pressure (=shock wave) generated from the induced explosion demonstrates that a considerable amount of the LOX/LNG mixture was exploded. Furthermore, the stainless steel pan containing the LOX/LNG mixture fragmented into small pieces. Both the generation of the shock wave and small pieces of fragments demonstrated that induced explosion is detonation. It is concluded that the LOX/LNG mixture is easily detonated, similar to a primary explosive.

References

1) K. Sato and Y. Kondou, Acta Astronautica, 59, 381−391 (2006).
2) A. G Streng, and A. D. Kirshenbaum, J. Chemical and Engineering data, 4, 127−131 (1959).
3) B. Leqis and G. von Elbe, Combustion, Flames and Explosions of Gases (Third Edition), p. 343, Academic Press (1987).
4) D. Kim, S. Usuba, Y. Watanabe, T. Nario, and Y. Kakudate, Science and Technology of Energetic Materials, 73, 47−52 (2012).
5) W. E. Baker, P. A. Cox and P.S. Westine, J. J. Kulesz, R. A. Strehlow, Explosion Hazards and Evaluation, p. 110, p. 207, Elsevier Science Publishing Company (1983)
6) G. I. Taylor, Proceeding of the Royal Society of London, Series A, Mathematical and Physical Sciences, 186, 273−292 (1946).
7) D. Kim, Sci. and Tech. Energetic Materials, 73, 20−21 (2012).
8) D. Kim, Sci. and Tech. Energetic Materials, 74, 50−52 (2013).