Letter

The study on the propagation behavior of flame and shock wave by image analysis

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Abstract

The propagation behaviors of the blast wave and the flame were investigated by optical measurement, when LOX and LNG falling freely onto the ground surface were exploded. The results of the image analysis showed that the propagation velocities of the flame and the blast wave were higher than the sound velocity. It was concluded that the explosion was the detonation, not the deflagration, although it was not happened all of this experiment. Furthermore, the arrival time and pressure value of the blast wave obtained by an image analysis were agreed with the measurement results by a piezoelectric pressure sensor.

Keywords: LOX, LNG, blast wave, detonation, image analysis

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1. Introduction

Recently, there are a lot of studies on the explosion strength of methane and oxygen[1)-4)]. One of studies[2)] found that LOX and LNG free falling from a height of 50 m will self-ignite when they come in to contact with each other. The previous study has reported that the minimum ignition energy is significantly small[5)], similar to a primary explosive. In terms of safety evaluation, our concern was whether the combustion of LOX and LNG by this self-ignition was deflagration or detonation. If the ignition is detonation, the flame propagation velocity must be higher than the sound velocity.

Background oriented schlieren (BOS)[6)-8)] is a well-known technique for optical measurements. The BOS method can be used with digital image analysis to investigate the propagation behaviors of a blast wave[6)]. In this study, the propagation behaviors of the flame and the blast wave were investigated using the digital images that were obtained by an optical measurement.

2. Previous experiment and image analysis method

For the image analysis, the previous experiment results[3)] were used. The experimental setup and the performance are presented by Kim et al.[2)] in detail. The previous study was conducted using two Dewar vessels, one containing LOX and the other containing LNG, fall freely onto the ground surface from the height of 50 m. The results confirmed self-ignition when LOX and LNG came into contact with each other.

A high-speed camera (Phantom v640, Vision Research Co.) recorded the explosion events at a rate of 10,000 fps. The distance between the explosion set-up and the camera was approximately 30 m. The length scale was based on the number of pixels, yielding a factor of 7.89 mm per pixel.

The positions of the flame front and the blast wave were estimated using digital image analysis. The image analysis was conducted by calculating the difference between two images with a time interval of 0.1 ms and subtracting the interval images.

First of all, the propagation velocity of the flame front was investigated to confirm the detonation or not. Next, the propagation velocity of the blast wave was investigated. The pressure value of the blast wave was estimated using the propagation velocity. The estimated

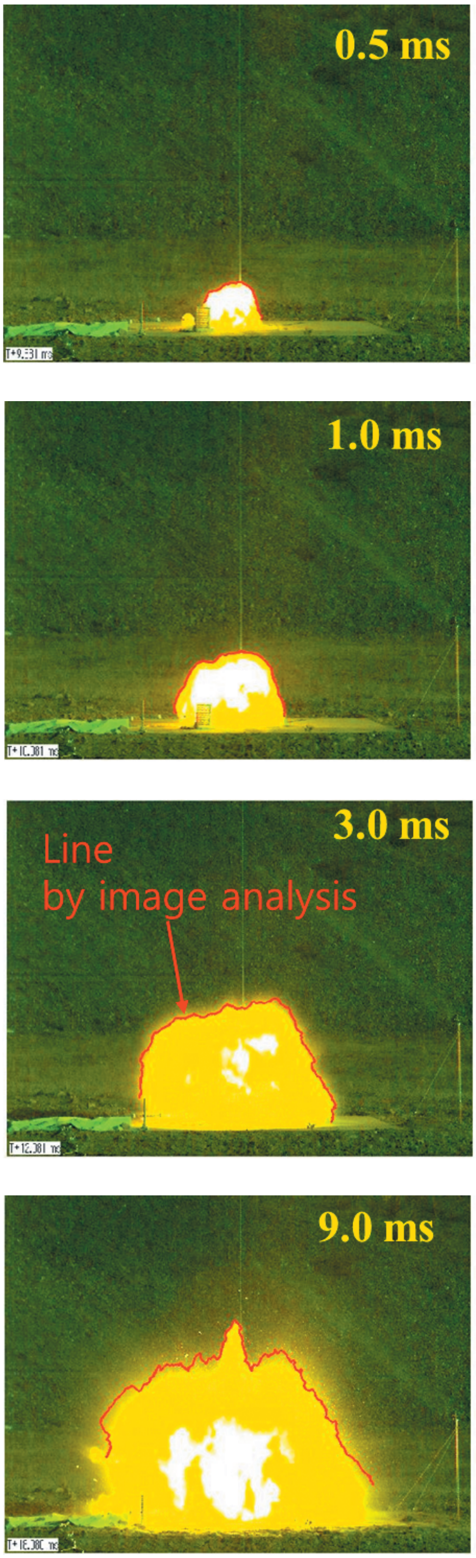

Figure 1 Framing images of flame for Exp. 2 with the line by the image analysis.

pressure was compared with the measurement results obtained by a piezoelectric pressure sensor. The setup for the measurement of blast wave pressure was the same as in the previous study[2),9)].

3. Results and discussions

3.1 Flame propagation behavior

Figure 1 shows the framing images obtained by a high speed camera after the ignition. The numbers in the

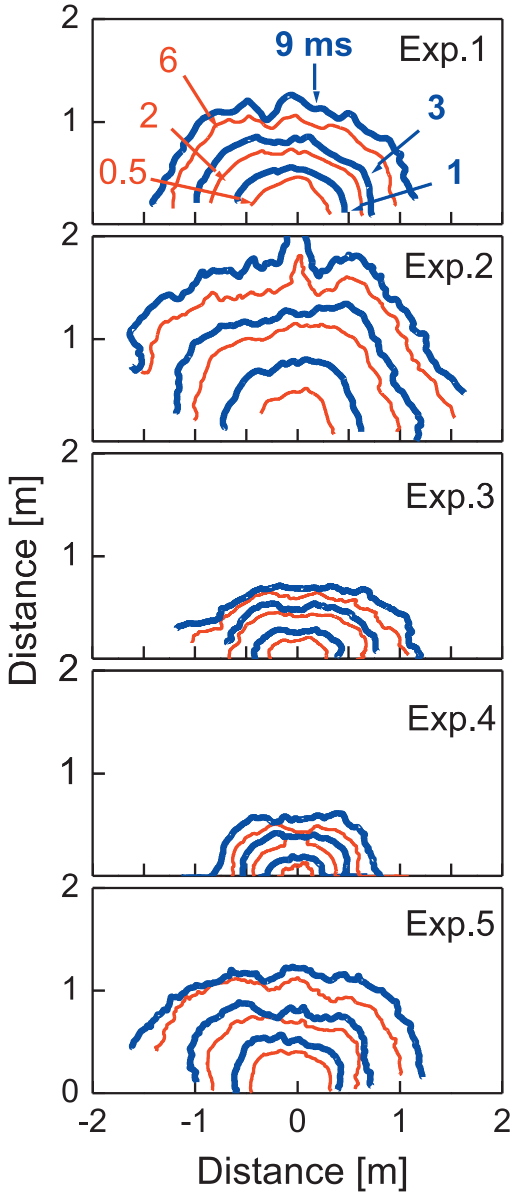

Figure 2 Analysis results of the framing images.

images represent the time after the ignition. The red lines were obtained by the image analysis; they clearly show the flame front propagation with time.

All of the results obtained by the images analysis are shown in Figure 2. Initial point (0,0) is the position where the vessels clashed with the ground surface. It was found that the flame front was not even and hence must be turbulence flow. Furthermore, the propagation velocities of the flame front were not the same. The horizontal velocity is higher than the vertical velocity.

In this study, the mean flame radius was obtained by the cross-sectional area integrated with the lines. The cross-sectional area was assumed to be half of the area of the cross section of the spherical shape. Figure 3 shows the flame propagation behaviors with time. Unfortunately, as it was not easy to fit the data accurately, so it was difficult to establish the velocity correctly. We were, however, able to at least confirm the order of velocity as follows; Exp.2 > Exp.5 ≥ Exp.1 > Exp.3 > Exp.4.

It is clear found that the flame front arrived more than 400 mm in 1 ms in Exp. 1, 2 and 5. Because the sound

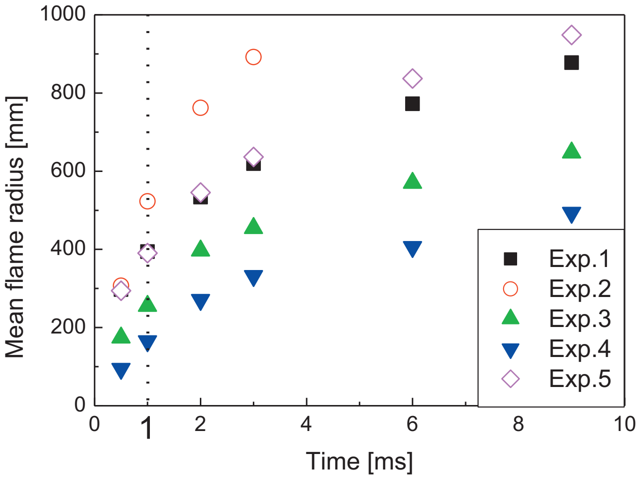

Figure 3 Flame propagation behaviors with time.

velocity of the stoichiometric gas mixture of methane and oxygen is lower than 400 m s^{-1}, it is clearly concluded that the explosion was detonation, not deflagration.

However, the velocity in Exp. 3 and 4 was lower than 300 m s^{-1}. It is assumed that the ignition was not detonation. It should be mentioned that all the experiment conditions were the same except for the collision plate. The collision plate in Exp.1 and 2 was aluminum alloy; however, in Exp.5 was stainless steel. It means that the change of the collision plate did not effect on the explosion behavior. Unfortunately, the reason behind this could not be clarified through this study. Thus, further research will be required.

3.2 Propagation behaviors of the blast wave

Propagation behaviors of blast waves were also studied using image analysis. For example, Figure 4 shows the image at 15.7 ms in Exp.2.

Although we do not presented the results of the measurement of blast wave pressure in this paper, time history of blast wave pressure using the piezoelectric pressure sensor shows that arrival time was 15.8 ms. Although we do not present the measurement results of blast wave pressure in this paper, we confirmed that the arrival time of blast wave obtained by the piezoelectric pressure sensor was almost the same to 15.8 ms.

Figure 5 shows the Mach number (M) versus the propagation distance for Exp.2. It should be mentioned that M is obtained using the sound velocity in air. It was found that the blast wave in this experiment was the shock wave because M was higher than one. The point of interest is that M (left axis) does not decrease continually. It is considered that the reason is the effect of the interference of the shock wave. As already shown in Figure 2, the flame propagation behaviors did not take the hemispheric form. Since the expansion of the burned gas did not form a hemisphere, the shock wave did not propagate in the hemispheric form either.

In this study, the estimated shock pressure (ΔP) was calculated using the following Equation (1) [6]

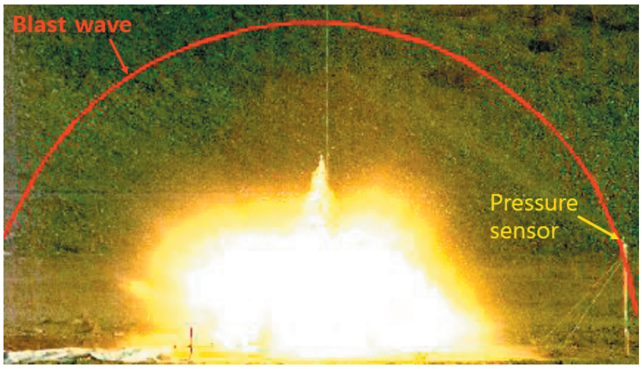

Figure 4 Flaming image with blast wave by BOS at 15.7 ms for Exp.2.

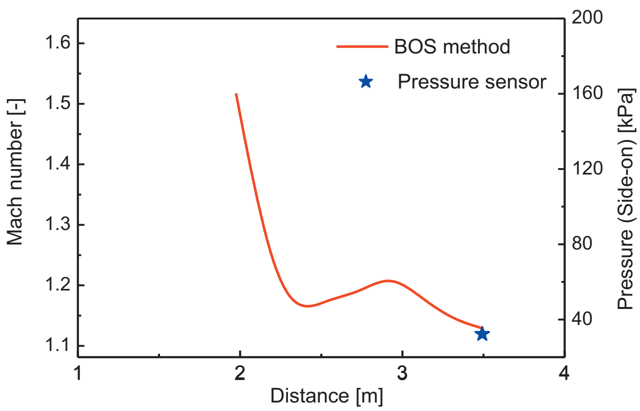

Figure 5 Mach number and pressure obtained using image analysis and measurement result of the piezoelectric pressure sensor.

$$\Delta P = 2\left(\frac{2\gamma}{\gamma+1}\right)(M^2-1)P_0, \quad (1)$$

where, γ is the heat capacity ratio as 1.4 and P_0 is the atmospheric pressure. The calculated values are shown in the right axis of Figure 5. It should be mentioned that M was obtained at the line from the clash point to the pressure sensor. The red line was obtained using the Equation (1). The blue symbol was the measurement result obtained by the pressure sensor.

When compared with the both results, the pressure value is almost the same. It is concluded that the optical measurement can be a reliable methodology to determine the blast wave pressure.

4. Conclusions

The propagation behaviors of the flame front and the blast wave were investigated using the image analysis, when self-ignition was induced by free falling LOX and LNG.

It was concluded that detonation was happened, although not in all the experimental setups the flame propagation velocities were higher than sound velocity.

The propagation behaviors of blast wave were also investigated. It is concluded that the blast wave from the self-ignition was the shock wave because the propagation velocity was higher than the velocity of sound wave. Furthermore, the results for the arrival time and the pressure level are almost the same as the measurement result obtained by the piezoelectric pressure sensor.

It is reconfirmed that image analysis of an optical measurement can be greatly helpful for the study of the explosion strength.

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