Relation between the ignition point of a flame and the jet behavior in a gas explosion

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1 Introduction

An explosion accident occurred at the Fukushima 1 nuclear power plant because of the Great East Japan Earthquake that occurred on March 11, 2011. A curing sheet , which deformed due to thermal influence, was found at the damaged part.

In a previous study, we investigated the heat effect on thermally thin combustibles by performing a small gas explosion experiment[1]. The behavior of the flame was observed by using thr Schlieren system. From this, it was confirmed that the unburnt gas ejected accelerated going away from the experimental vessel, and the flame decelerated. In this study, we changed the ignition point of the experiment vessel, and its effect on the behavior of the flame was examined.

2 Overview of the experimental

In this study, ethanol was volatilized in an experimental vessel. Then, it was ignited by spark ignition, and the injected flame was observed with the Schlieren system. In the experiment, 0.1 mL of ethanol was used as fuel. In consideration of safety, the experiment was conducted without closing the experimental vessel. Figure 1 shows a schematic of the Schlieren system. The Schlieren system consists of a light source (light emitting diode), concave mirror, knife edge, high-speed camera. In the schlieren system, light from a point light source is irradiated to a concave mirror to become parallel light, and it is passes through an observation portion. The light condensed at the focal point is partially shielded by the knife edge, and the observation

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portion is imaged by the lens. When there is a temperature difference in the observation portion, the optical path of the light is changed by the density gradient. damaged part.

Figure 2 shows the outline of the experimental vessel used in the experiment. The dimensions of the cylindrical experimental vessel are an internal diameter of *L* = 40.8 mm, and a depth of 51 mm. A window is attached to the side of the experimental vessel, so that the interior of the container can be observed. The spout of the experimental vessel is a circle of diameter *d* = 25.5 mm and length *l* = 27.38 mm. The volume *V* in the experimental vessel is 7.96×10^{-2} L, and the distance from the center of the spark ignition electrode to the tip of the flame is *R*. As the ignition point of the experimental vessel, three vessels shifted by 10 mm above and below the center part of the container were prepared and experiments were carried out in each. Figure 3 shows the location of the ignition point.

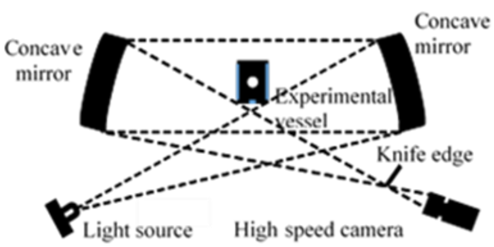


Figure. 1 Schematic of schlieren system

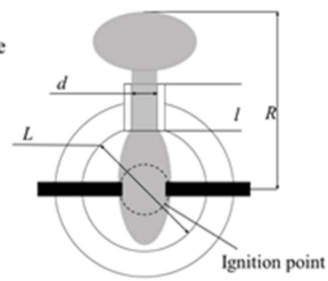


Figure. 2 Experimental vessel

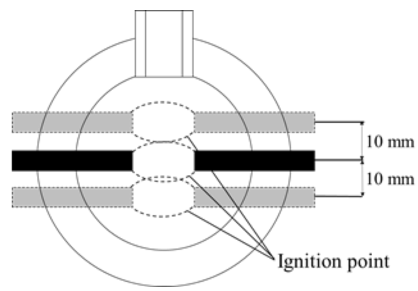


Figure. 3 Ignition point of the experimental vessel

3 Expression related to spherical shock wave and energy

Taylor reviewed the propagation and damping of atmospheric blast in the paper [2], [3]. A similar source solution of the point source explosion was converted as follows.

pressure $$\frac{p}{p_0} = y = R^{-3} f_1 \quad (1)$$

density $$\frac{\rho}{\rho_0} = \Psi \quad (2)$$

radial velocity $$\mathrm{u} = R^{-3} \varphi_1 \quad (3)$$

where *R* is the blast radius, p_0 and ρ_0 are the atmospheric pressure and density.

The equation of motion is $$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\frac{p_0}{\rho} \frac{\partial y}{\partial r} \quad (4)$$

The equation of countinuity is $$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r} + \rho\left(\frac{\partial u}{\partial r} + \frac{2u}{r}\right) = 0 \tag{5}$$

The equation of state for a perfect gas is $$\left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial r}\right)(p\rho^{-\gamma}) = 0 \tag{6}$$

From the equations (4)-(6), the following equation for the spherical shock wave can be obtained.

$$\frac{d\mathrm{R}}{dt} = AR^{-\frac{3}{2}} \tag{7}$$

where *t* is the time since the explosion began. *A* is a constant. When both sides of the equation (7) are arranged and integrated,

$$\frac{2}{5}R^{\frac{5}{2}} = A(t - t_0) \tag{8}$$

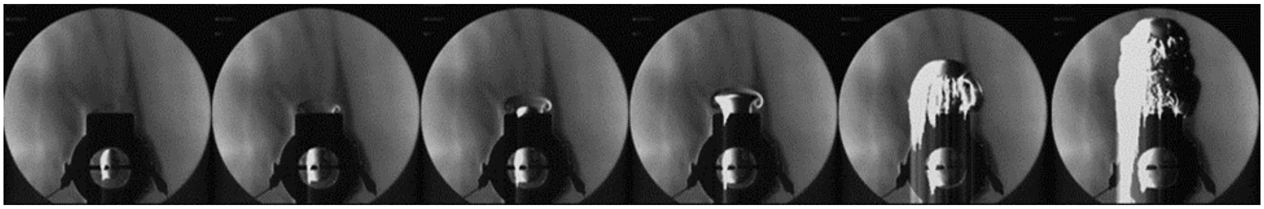
For the explosion of large energy, the calculation formula of the total energy *E* which is the sum of kinetic and thermal energy, were set as follows.

$$E = 5.36\rho_0 A^2 \tag{9}$$

4 Schlieren photograph

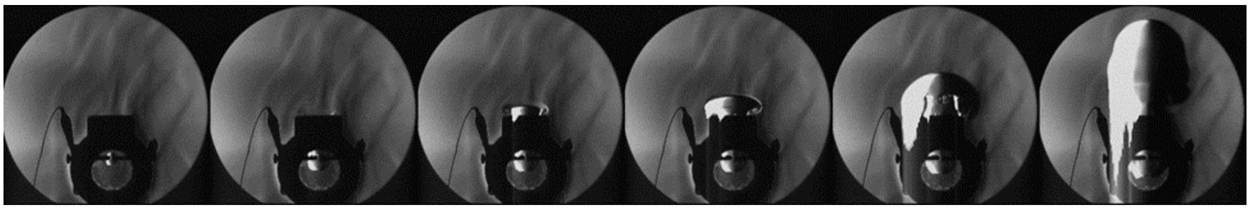
The condition where the flame is jetted from the experimental container was taken by Schlieren system. The shooting conditions were 1000 FPS and the exposure time was 1/20000 s. Figure 4 shows the Schlieren image when the ignition point was in the center of the experimental vessel, Figure 5 shows the case where the ignition point was high, and Figure 6 shows the case where the ignition point was low. *t* is the elapsed time since the explosion began. Regarding the behavior of the flame under all the conditions, the following were confirmed. 1) spread inside the experimental vessel after ignition. 2) propagation of the inside of the unburnt gas was ejected first. 3) after catching up with unburned gas, it progresses upward. vessel.

Comparing the three conditions, the flame propagation speed was smaller when the ignition point was higher compared with the other two conditions. Focusing on how to propagate the flame, the flame was burning and spreading over almost the entire area in the experimental container when the ignition point was at the center and low. However, when the ignition point is high, the inside of the experimental container was not burning sufficiently. In addition, when comparing the jetted flames, there were many wrinkles when the ignition point was in the center and in the low, whereas when the ignition point was high, almost no wrinkles were detected.



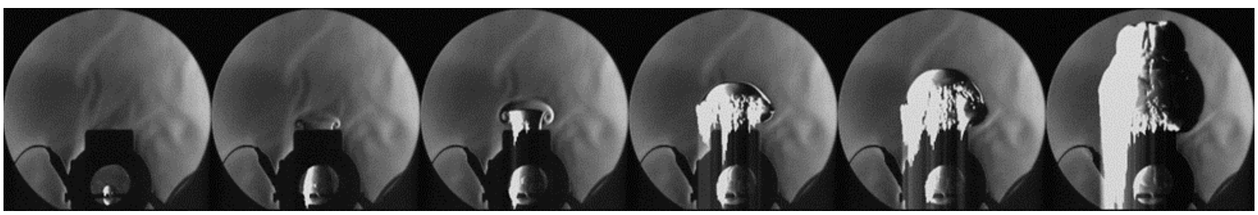
t = 0.006 (s) *t* = 0.008 (s) *t* = 0.009 (s) *t* = 0.010 (s) *t* = 0.013 (s) *t* = 0.017 (s)

Figure. 4 Ignition point is in the center of the experimental



t = 0.006 (s) *t* = 0.016 (s) *t* = 0.019 (s) *t* = 0.021 (s) *t* = 0.029 (s) *t* = 0.057 (s)

Figure. 5 Ignition point is in the high of the experimental



t = 0.004 (s) *t* = 0.008 (s) *t* = 0.010 (s) *t* = 0.012 (s) *t* = 0.013 (s) *t* = 0.018 (s)

Figure. 6 Ignition point is in the low of the experimental

5 The trajectory of the flame

In Taylor's study, shock waves generated by an explosion were analyzed. However, in this experiment, a shock wave could not be observed. Therefore, in this study, the tip of the flame and unburned gas was plotted.

A graph of the relationship between *R* and *t* at each ignition point in flame and unburned gas is shown, Figure 7 shows a graph of the flame, and Figure 8 shows a graph of the unburned gas. The vertical axis is distance *R* (mm) and the horizontal axis is time *t* (s). In the experiment, the conditions were the same at each

ignition point, and each was conducted five times. Figure 7 shows that when the ignition point was high, the propagation speed of the flame was very slow compared with other condition. However, when the ignition point was high, the flame propagation speed decreases as the trajectory of the flame tip advanced. When the ignition point was low, there was little difference in the jetting speed in each experiment.

Figure 8 shows that there was not much difference in the ejection speed of unburnt gas under all the conditions. Next, a graph of the relationship of *R* to the power of 5/2 and t is shown. The flame is shown in

Figure 9, and unburnt gas is shown in Figure 10. The 5/2-th power of *R* was taken on the vertical axis, and *t* was taken on the horizontal axis. As shown in Figure 9, it became almost linear under all conditions. However, as shown in Figure 10, it gently increased with all conditions. In this experiment, an analysis was conducted at the tip of the flame instead of the shock wave, but the result agreed with the experimental results of Taylor.

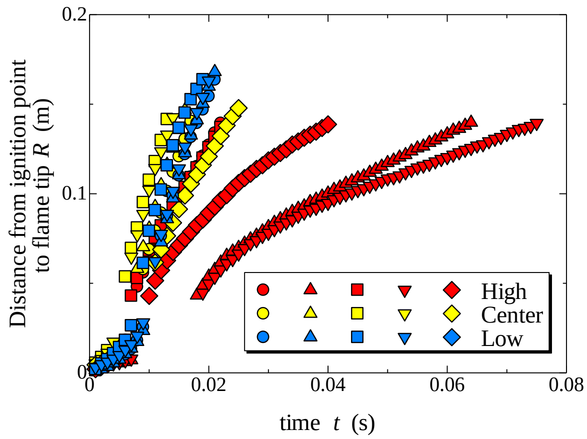


Figure.7 Flame front radius with time

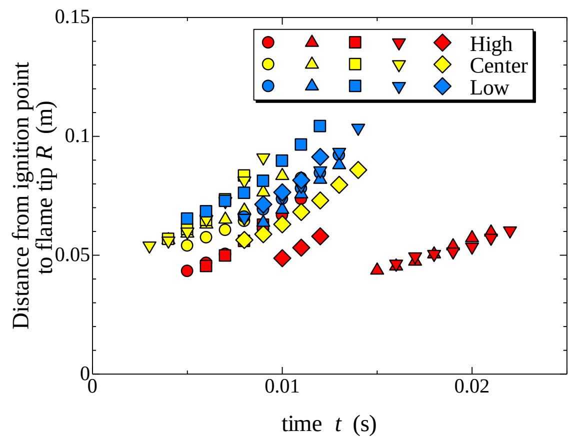


Figure.8 Ejection velocity and time of unburnt gas

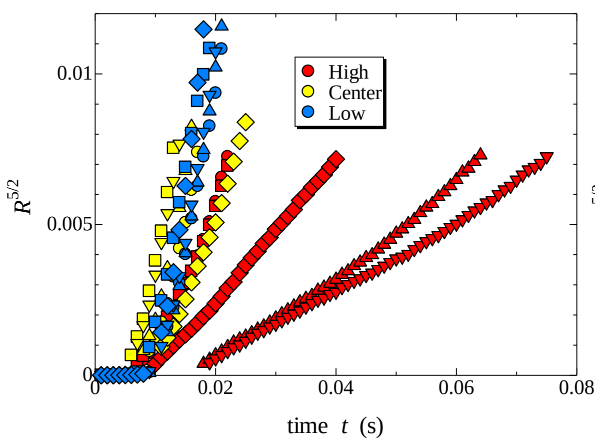


Figure.9 Relationship between $R^{\frac{5}{2}}$ and time in flame

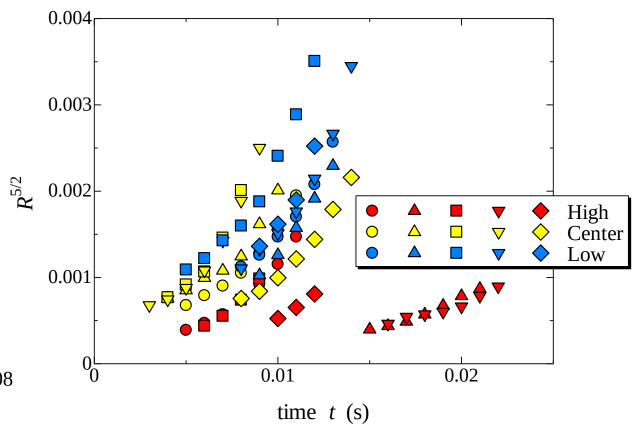


Figure.10 Relationship between $R^{\frac{5}{2}}$ and time in unburnt gas

6 Conclusion

The following facts were found in this study.

(1) When the experiment was conducted by changing the height of the ignition point, the flame propagation speed was very small when the ignition point was high.

(2) The ejection velocity of unburnt gas is not much affected by the ignition point.

(3) For $R^{\frac{5}{2}}$, the graph of the flame propagation velocity becomes almost linear. On the other hand, it did not become a straight line at the ejection velocity of unburnt gas.

7 References

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[2] Geoffrey Taylor. The Formation of a Blast Wave by a Very Intense Explosion 1 Theoretical Discussion. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. Vol.201. No. 1065. (Mar. 22, 1950). pp. 159-174

[3] Geoffrey Taylor. The Formation of a Blast Wave by a Very Intense Explosion 2 The atomic explosion of 1945. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 201, No. 1065. (Mar. 22, 1950), pp. 175-186.