Experimental Study on Behavior of Methane/Oxygen Gas Detonation near Propagation Limit in Small Diameter Tube : Effects of Equivalent Ratio

Keisuke Yoshida*, Taku Inoue*, Youhi Morii**, Kiyoto Murakami*,

Nobuyuki Tsuboi*, and A. Koichi Hayashi***

* Kyushu Institute of Technology,1-1, Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka, 804-8550, Japan

**Japan Aerospace Exploration Agency, 3-1-1,Yoshinodai, Chuo-ku, Sagamihara,Kanagawa, 252-5210, Japan

***Aoyama Gakuin University 5-10-1, Fuchinobe, Chuo-ku, Sagamihara, Kanagawa, 252-5258, Japan

1 Introductions

The detonation propagating limit is an important fundamental and practical problem from an engineering safety point of a view. The detailed structures and properties of the detonation have been studied using the experimental and the numerical methods. However, a theory for the prediction of the detonation limits does not exist. The detonations in a circular tube were measured to observe a few modes, for example, single-head spinning, two-headed, and multi-head. The single-head spinning is the lowest mode in the limit mixtures in a circular tube to propagate with a helical track on the wall and to rotate around the tube axis. This detonation is an important issue in predicting the detonation limits. Therefore, the limit range of the single-head spinning has to be clear. Campbell and Woodhead [1-3] first discovered single-head spinning in a stoichiometric mixture of carbon monoxide and oxygen in 1926. The effects of mixture composition on single-head spinning were described by Gordon [4] and Barthel [5]. Achasov and Penyazkov [6] also investigated the evolution of detonation cell structure of a gaseous detonation including single-head spinning in a circular tube as a function of the initial pressure. With regard to galloping detonation, Duff et al. [7] reported that the detonation re-ignites and propagates after single-head spinning detonation quenches. In some cases, the detonation velocity fluctuates near the propagation limit condition. According to the oscillations of the detonation velocity, Lee et al. [8] classified the propagation into six types of modes. Those six modes were stable, rapid fluctuation, stuttering, galloping waves, fast flames and failure. Susa et al. [9] reported that the oscillation of galloping detonation is dependent on the initial conditions. Gao et al. [10]

Correspondence to: yoshida.keisuke32@gmail.com

investigated that galloping detonation are not always observed in all mixtures and in all tube diameters. We reported the effect of the tube diameter for the detonation propagating limit. [11] There are few reports about the effect of the equivalent ratio near propagating limits.

The purpose of this study is to obtain the knowledge on the unstable phenomenon of detonation near the propagation limit by using the data from records of smoked foil experiments and detonation velocity measurements in methane/oxygen gas mixture for various initial pressures and equivalent ratios.

2 Experimental details

Figure 1 shows the schematic diagram of the experimental apparatus. The apparatus mainly consists of the detonation tube made of PYREX® glass, a stainless steel ignition chamber, a sample gas mixing tank, and a high-voltage power supply line for a spark ignition, respectively. Self-luminescence of the detonation front was captured by optical fibers (OFS Specially Photonics Division; All Silica 365, core clad of 400 μm with numerical aperture of 0.22), which were placed along the quartz tube at 100 mm intervals. Total of 25 fibers were placed and connected to the photoelectric surface of a photo-multiplier (PMT: HAMAMATSU R1527). Sharp peaks were obtained as a consequence of the narrow view angle of the optical fibers, as shown in Fig. 2. Detonation velocities were calculated by the intervals of the peaks, as shown in Fig. 2. The premixed sample gas was prepared in a stainless mixing tank. After evacuating the tank by the rotary pump, methane and oxygen gases were supplied into the tank up to 80.0 kPa and the mixture gas was kept at this level about one day to become complete mixing of gases through diffusion. The gas purity was 99.9% for the methane (Kyushu Sanso Corp.) and 99.99995% for the oxygen (Kyushu Sanso Corp.). The pressure of the gas line was monitored by a capacitance manometer (Nagano Keiki Corp.). The thin smoked foils for recording the detonation cell pattern are prepared using a lamp or candle on Mylar film with a 50 μm thickness that had been cut into a predetermined size in advance. Before the ignition, the smoked foil was inserted into the glass tube. The glass tube and the ignition chamber were evacuated for more than 30 minutes to obtain a high vacuum condition for a high voltage discharge. Next, the pre-mixed gas was supplied into the glass tube from the mixing tank. Then, we ignited the combustible mixture by a spark discharge between needle electrodes using a high-voltage power supply. The experimental conditions are shown in Table 1.

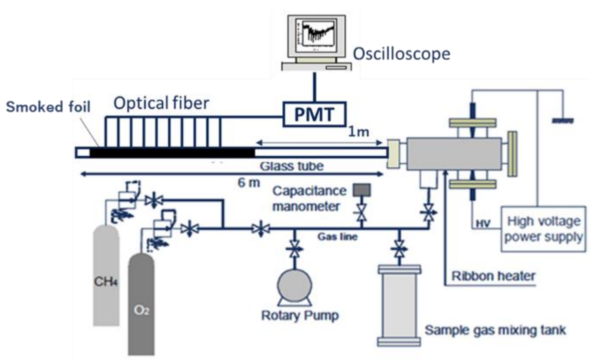


Figure 1 Diagrammatic illustration of experimental apparent.

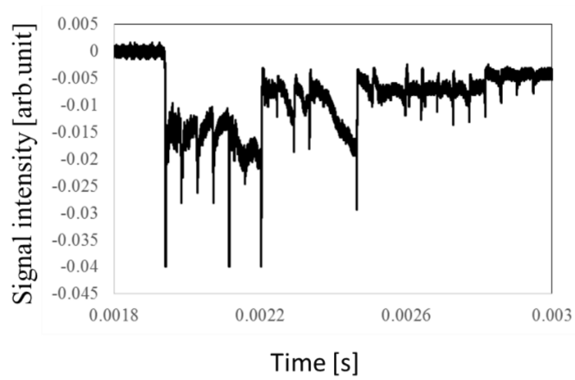


Figure 2 Self-luminescence peaks of propagating detonation.

Table 1 Experimental conditions.

Sample gas	CH_4/O_2
Temperature: T	298±5 K
Tube diameter: *d*	5.8 mm
Initial pressure: P_0	10-35 kPa
Equivalent ratio: φ	0.6, 0.8, 1.0, 1.2, 1.4
smoked foil size (Width x Length)	18 x 2400 mm
α (= $\pi d/\lambda$)	0.2 - 1.6

3. Results and Discussions

3.1 Velocity measurements

In Fig. 3, the comparison of the detonation velocities for various equivalent ratios is shown. The non-dimensional parameter α is defined in the following equation (1):

$$\alpha = \frac{\pi d}{\lambda} \tag{1}$$

Therefore, α is the ratio of circumference and the detonation cell width. The upper bars of these plot mean the local maximum value in its case, and the under bars mean the minimum value. Regardless of the equivalent ratio, the experimental detonation velocity is 60 - 80 percent of the C-J velocity for $\alpha < 1.0$. On the other hand, the detonation average velocities correspond to the theoretical C-J velocity for all equivalent ratios.

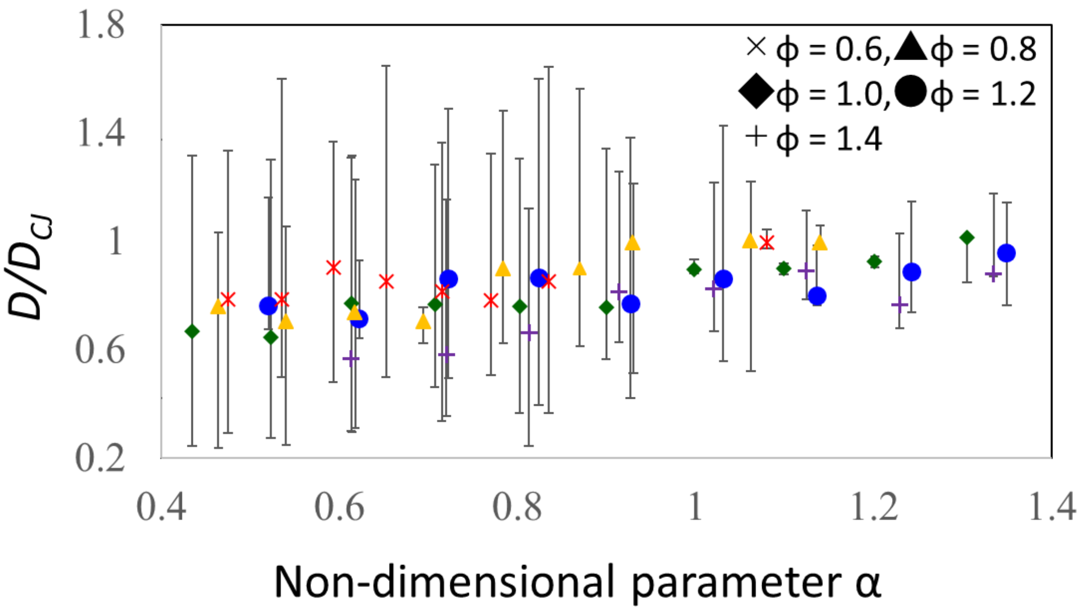


Fig. 3 Average detonation velocities for various equivalent ratios.

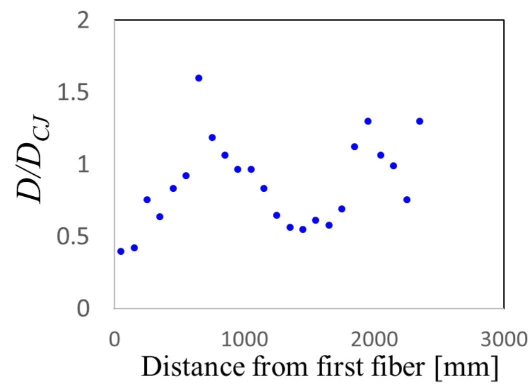


Fig. 4 Oscillation of detonation velocity for φ = 1.2 and P_0 = 20 kPa. (α = 0.8)

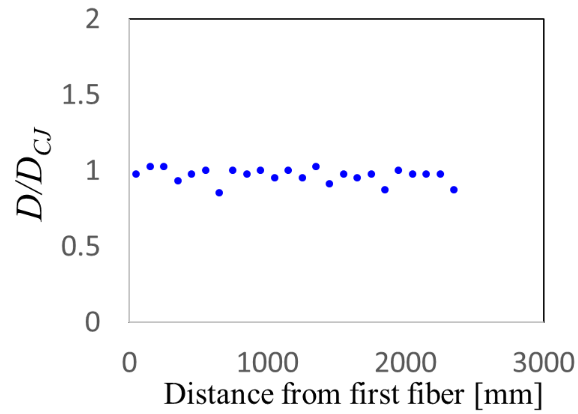


Fig. 5 Oscillation of detonation velocity for φ = 1.2 and P_0 = 34 kPa. (α = 1.8)

For α < 1.1, the difference between the maximum and minimum values is very large. The behaviors of the detonation velocities are unstable. For α > 1.1, the difference between the maximum and the minimum values is small. The behaviors of the detonation velocities are stable. In Fig. 4, the oscillation of the detonation velocities for α < 1.0 is observed. The detonation velocities vary between 0.2 D_{CJ} and 1.6 D_{CJ}. The average value of the detonation velocities is 1880 m/s, which is 30 % smaller than C-J velocity in this condition. The oscillation of the detonation velocities for α > 1.0 is shown in Fig. 5. The average velocity becomes the C-J velocity, and its oscillation becomes 10 % of the C-J velocity. In the next section, the cell structure of the detonation is discussed to understand the feature and the low-velocity propagation and the reason for the oscillations in the detonation velocities. The oscillation of the detonation is decided from non-dimensional parameter α.

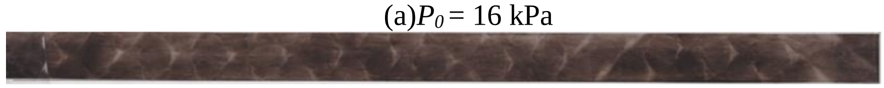
4.2 Cellular patterns

For P_0 = 16 kPa in Fig. 6 (a), small cells are observed in the beginning of the smoked pattern and the size of cell patterns gradually increase. Then, the cellular patterns disappear. For P_0 = 34 in Fig. 6 (b), the cell patterns repeat between the multi-head and the single-head spinning. In this case, the cellular patterns of the detonation do not disappear and its propagates to the final of smoked foil region. In the other equivalent ratio, similar results were observed. The propagating mode is independent of the equivalent ratio. However, the propagating mode depends on the non-dimensional parameter α.

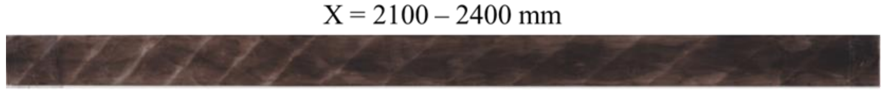
X = 2100 – 2400 mm

X = 2400 – 2700 mm

(a)P_0 = 16 kPa



X = 2100 – 2400 mm



X = 2400 – 2700 mm

(b)P_0 = 34 kPa

Fig. 6 Cellular patterns for φ = 1.4.

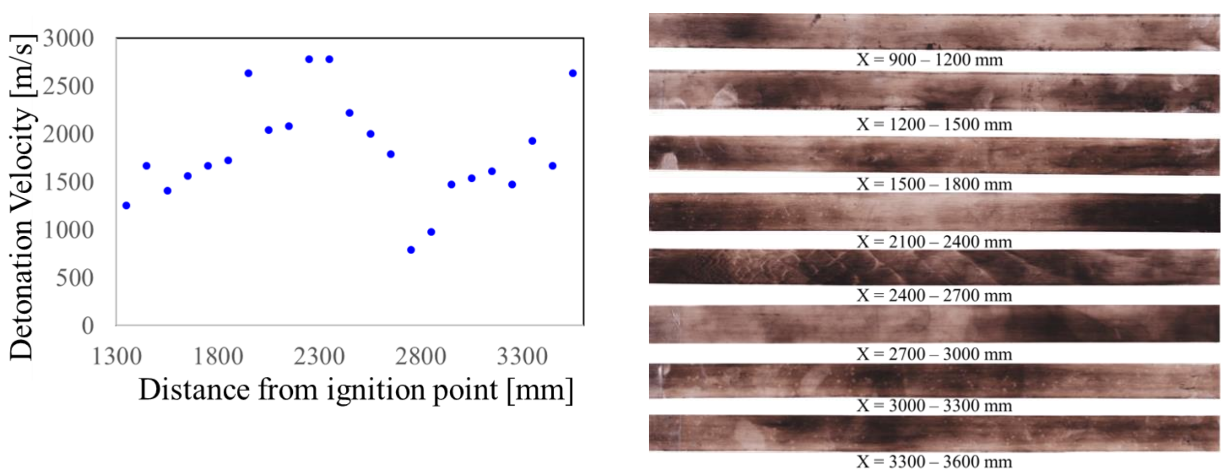
Table 2 Comparison of equivalent ratios for failure map(o : failure of cellular patterns, x: propagating with cellular patterns).

	Equivalent ratio[-]				
	0.6	0.8	1.0	1.2	1.4
$\alpha = 0.5$	o	o	o	o	o
$\alpha = 0.8$	o	o	o	o	o
$\alpha = 1.2$	x	x	x	x	x and o
$\alpha = 1.4$	x	x	x	x	x

The comparison of the equivalent ratios for failure map is shown in Table 2. For $\alpha < 1.0$, patterns disappear. For $\alpha > 1.0$ and the all equivalent ratio, the detonation propagates with the cellular patterns. However, the stable and unstable propagations are observed for $\varphi = 1.4$ and $\alpha = 1.2$. The parameter α is important in determining the propagation mode for the gaseous detonation near the propagation limit.

4.3 Relation between detonation velocity and cellular patterns

Figure 7 shows the result of the simultaneous measuring between the oscillation of the detonation velocity and the cellular patterns. The appearance of the cellular structure is observed under the overdriven velocity region. In the region where the cellular structure is not observed, the experimental detonation velocities become smaller than the C-J velocities. The oscillation of the detonation velocities is due to the instability of the cell patterns. The unstable situation in the cellular patterns corresponds to large variations in the detonation velocity. The re-ignition and disappearance causes the variation in the detonation velocity for $\alpha < 1.0$.



(a) Detonation velocity (b) cellular patterns

Fig. 7 Simultaneous measuring between oscillation of detonation velocity and cellular patterns.

4. Conclusions

The experimental study measured the characteristics of the detonation propagation limit in methane/oxygen gas mixture in the round tubes with various equivalent ratios. The major conclusions are summarized as follows:

a) The behavior of the detonation velocities is unstable for $\alpha < 1.0$ and all equivalent ratios. The detonation velocities vary between 0.2 D_{CJ} and 1.6 D_{CJ}.
b) The cellular patterns for $\alpha < 1.0$ and all equivalent ratios are unstable. The disappearance and re-appearance were observed, therefore, it is suggested that the propagating mode is the galloping detonation.
c) The unstable situations of the cellular patterns correspond to large variation of the detonation velocity. The criterion $\alpha = 1.0$ is important in dividing the features of detonations near the detonation propagation limit. This criterion means that the detonation cell width is equal to the inner perimeter of the tube.

References

[1] Campbell C. and Woodhead D.W. 1926. The Ignition of Gases by an Explosion Wave I. Carbon Monoxide and Hydrogen Mixtures. J. Chem. Soc., pp.3010-3021.

[2] Campbell C. and Woodhead D.W. 1927. Striated photographic records of explosion waves. J. Chem. Soc., pp.1572-1578.

[3] Campbell C. and Finch A.C. 1928. Striated photographic records of explosion waves 2. An explanation of the striae. J. Chem. Soc., pp.2094.

[4] Gordon W.E., Mooradian A.J. and Harper S.A. 1959. Limit and Spin Effects in Hydrogen-Oxygen Detonations. Proc. Comb. Inst. 7, pp. 752.

[5] Barthel H.O. (1974). Predicted spacings in hydrogen-oxygen-argon detonations. Phys. Fluids 17, pp.1547.

[6] Achasov O.V. and Penyazkov O.G. 2002. Dynamics study of detonation-wave cellular structure. 1. Statistical properties of detonation wave front. Shock Waves 11, pp.297.

[7] Duff R.E., Knight H.T. and Wright H.R. 1954. Some Detonation Properties of Acetylene Gas. J. Chem. Phys. Vol. 22, pp. 1618-1619.

[8] Lee J. J., Dupre G., Knystautas R. and Lee J. H. 1995. Doppler Interferometry Study of Unstable Detonation. Shock Wave Vol.5, pp. 175-181.

[9] Susa A., Hasegawa S., Yokoyama H., Endo T. 2011. Oscillating propagation of near-limit detonations of CH4/O2 system in a small diameter tubes. Proceedings of the 23rd ICDERS.

[10] Gao Y., Lee J.H.S. and Ng H. D. 2014. Velocity fluctuation near the detonation limits. Combustion and flame Vol.161, pp.2982-2990.

[11] Yoshida K., Hayashi K., Morii Y., Ttsuboi N., Hayashi A. K. 2016. Behavior of Methane/Oxygen Gas Detonation near Propagating Limit in Small Diameter Tube: Effect of Tube Diameter. Combustion and Science Technology Vol. 188. pp. 2012-2025.