Behavior of Methane/Oxygen Gas Detonation near Propagating Limit in Small Diameter Tube:Effect of Tube Diameter

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1 Introduction

Detonation propagating limit is an important fundamental and practical problem for safety engineering point of view. The detailed structures and properties of the detonation have been studied using the experimental and numerical methods. However, the theory for predict detonation limits does not exist. The smoked foil technique [1-3] has been widely used to record the variations of the cellular patterns in the study of the gaseous detonations. The detonations in a circular tube were measured to observe a few modes, for example, the single-spinning mode, the two-headed mode, and the multi-headed mode. The single spinning mode 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. The single-spinning mode is an important issue to predict detonation limits. Therefore, the limit range of the single-spinning mode has to be found. Campbell and Woodhead [4-6] first discovered the single-spinning mode in a stoichiometric mixture of carbon monoxide and Oxygen in 1926. The effects of the composition of the mixture on the single-spinning mode were described by Gordon [7] and Barthel [8]. Achasov and Penyazkov [9] also investigated the evolution of cellular structure of a gaseous detonation including the single-spinning mode in a circular tube as a function of the initial pressure. Kitano et al. [10] reported that propagating mode change from the multi-head mode to the single-spinning mode near the propagation limit of Hydrogen/Oxygen detonation. Tsuboi et al. [11-13] and Kurosaka et al. [14] investigated the structure of the single spinning mode with computational fluid dynamics. Although there existed many past studies about the spinning mode, few experimental data about spinning mode in Methane/Oxygen gas mixture are obtained. With regard to the galloping detonation, Duff et al. [15] reported that detonation reignites and propagates after the spinning detonation quenches. In some cases, the detonation velocity fluctuates near the propagating limit condition. According to the oscillations of the detonation velocity, Lee et al. [16] classified propagating mode into six types of modes. Those six modes were stable, rapid fluctuation, stuttering, galloping waves, fast flame and failure. Gao et al. [17] investigated that the galloping mode are not always observed in all mixtures and in all tube diameters. The purpose of this study is to obtain the knowledge on the single-spinning mode and the feature of the detonation near the detonation limit by using the smoked foil records in Methane/Oxygen gas mixture for various initial pressures and tube diameter.

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2 Experimental details

Figure 1 shows the schematic diagram of the experimental apparatus. This apparatus mainly consists of the detonation tube made of PYREX® glass, the stainless ignition chamber, the sample gas mixing tank, and the high-voltage power supply line for the spark ignition, respectively. In this study, we used three kinds of the detonation tube in different inner diameter. The first detonation tube is nearly 6 m in length and 5.8, 8, and 10 mm in inner diameter. The second detonation tube is nearly 6 m in length and 8 mm in inner diameter. The premixed sample gas is prepared in the stainless mixing tank. After evacuating the tank by the rotary pump, Methane and Oxygen gas are introduced into the tank up to 80.0 kPa and the mixture gas is kept about one day to become complete mixing of gases by diffusion. Gas purity was 99.9% for Methane gas (Kyushu Sanso Corp.) and 99.99995% for Oxygen gas (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 smoked foil pattern are prepared. This was generated using a lamp or candle on the Mylar film 50 μm in thickness which had been cut into a predetermined size in advance. Before ignition, the smoked foil was inserted into the glass tube, and the glass tube and the ignition chamber are evacuated for more than 15 minutes to obtain a high vacuum condition for a high voltage discharge. Next, the pre-mixed gas was introduced into the glass tube from the mixing tank. Then we ignited by a spark discharge between the needle electrodes using a high-voltage power supply. After the experiment, the smoked foil inserted into the glass tube was collected as smoked foil patterns, and we checked the cellular structure on the smoked foil. The conditions in this study are shown in Table 1.

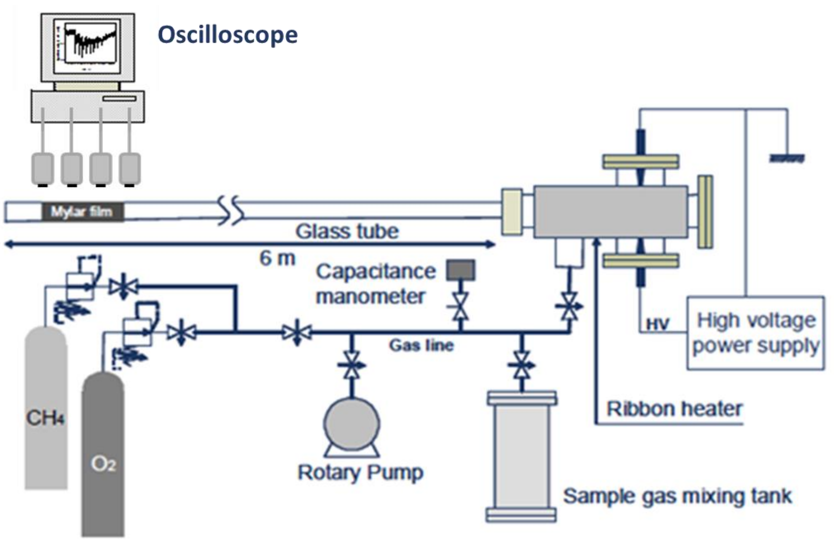

Fig.1 Schematic diagram of the experimental apparatus.

Table 1: Experimental conditions

	CASE A	CASE B	CASE C
Sample gas	CH4+O2		
Temperature [K]	293±5		
Initial pressure [kPa]	5-35		
Equivalent ratio	1.0	1.0	1.0
Tube diameter [mm]	10.0	8.0	5.8
Short smoked foil size [mm] Width x Length	30x300	24x300	18x180
Long smoked foil size [mm] Width x Length	30x1200	24x900	

3 Results and discussions

In this study, the value of Cell width λ is given by the following equation:

$$\lambda = 827 P_0^{-1.2}$$

where, λ means cell width [mm] and P_0 means initial pressure [kPa], respectively. This equation is approximate expression derived by the experimental cell width λ in detonation database [18].

3.1 Velocity measurement

The results of the velocity measurement for *d*=5.8, 8.0, and 10.0 mm versus *πd/λ* are shown in Figs. 2-4. The error bars in these figures mean the maximum and minimum values of the velocity in each conditions. The velocities equal to the theoretical C-J values in *πd/λ* > 1.0 for CASE A. However, the velocity decreases rapidly in *πd/λ* >1.0 and it becomes 60-80 % of C-J velocity. For CASE B and πd/λ > 1.0, the detonation velocity is approximately 95 % of C-J value. The detonation velocity is 60-80 % of C-J velocity in *πd/λ* < 1.0, however, it becomes 95 % of C-J velocity in *πd/λ* > 1.0 for CASE C. Figure5 shows the comparison of CASE A, B and C. Regardless the tube diameter, the detonation velocity is less than the 80 % of C-J velocity as *πd/λ* < 1.0. As *πd/λ* > 1.0, the detonation velocity is correspond to the theoretical C-J velocity for CASE A, and is around 95 % of C-J velocity for CASE B and C.

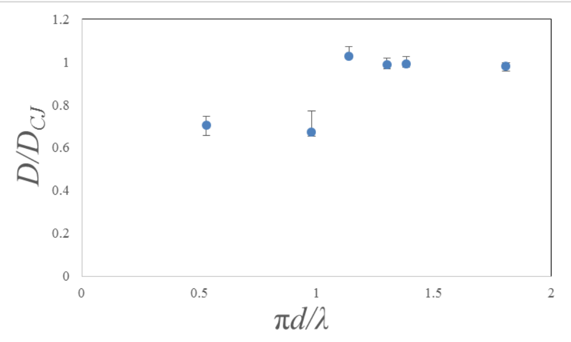

Fig.2 Velocity measurement for CASE A (*d*=10.0).

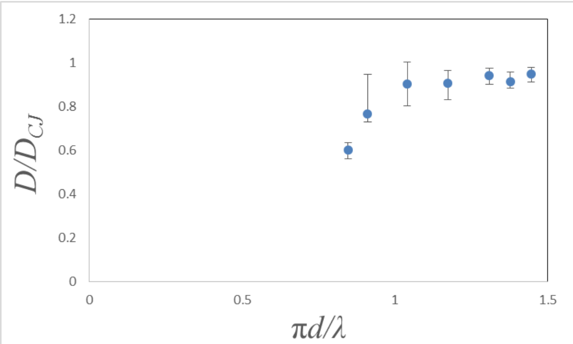

Fig.3 Velocity measurement for CASE B (*d*=8.0).

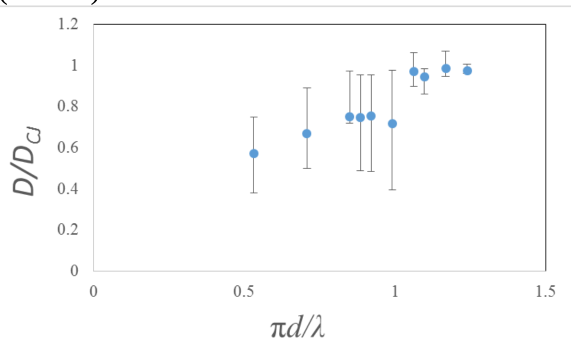

Fig.4 Velocity measurement for CASE C (*d*=5.8).

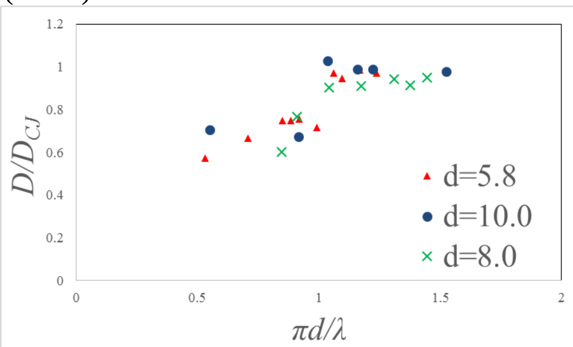

Fig.5 Summary of velocity measurement for various tube diameters.

3.2 Cellular patterns

The cellular patterns are classified into three different patterns, which are the small cells, the single-spinning mode and the multi-headed mode. The small cells mean that there exists small and increment size of the multi-headed cell patterns on the smoked foil record. The cell size of the small cells is not a constant value. The smoked foils to obtain in this study are shown in Fig.6 for CASE C. As the initial pressure is lower than 28 kPa, the small cells were obtained on the smoked foil record. The propagation mode was the single-spinning mode for 29 kPa < P_0 <32 kPa. The multi-headed mode was observed as the initial pressure P_0 is larger than 33 kPa. CASE A and CASE B showed a similar result of CASE C. In CASE A, the small cells were observed for P_0 < 15 kPa and in CASE B, for P_0 < 17 kPa. The relation between the propagation mode and $\pi d/\lambda$ is shown in Fig.7 for CASE A, CASE B and CASE C. The existing range of the single-spinning mode is $\pi d/\lambda$ > 1.0 and this is independent of the tube diameter. For $\pi d/\lambda$ < 1.0, the cellular patterns were the small cells for all of this case. The parameter $\pi d/\lambda$ is important to decide the propagating mode of the gaseous detonation.

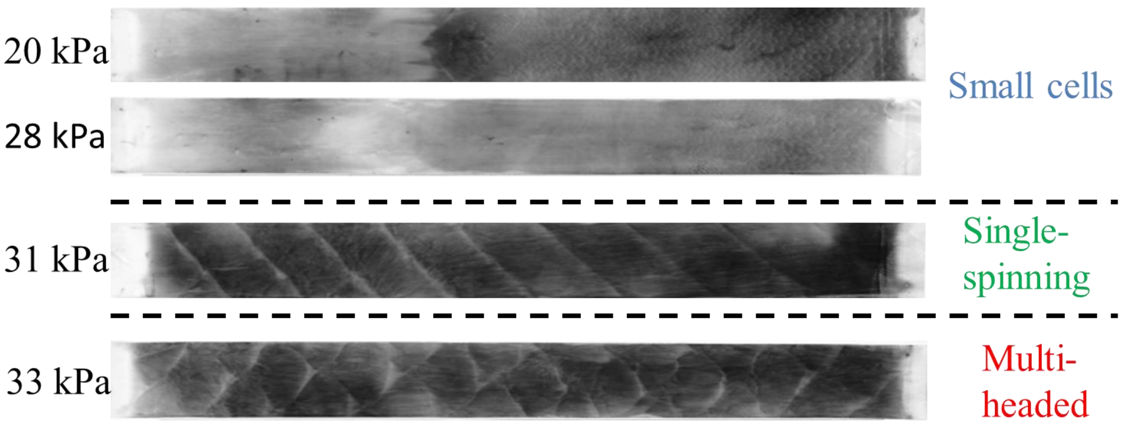

Fig.6 Smoked foil patterns using short foil for CASE C.

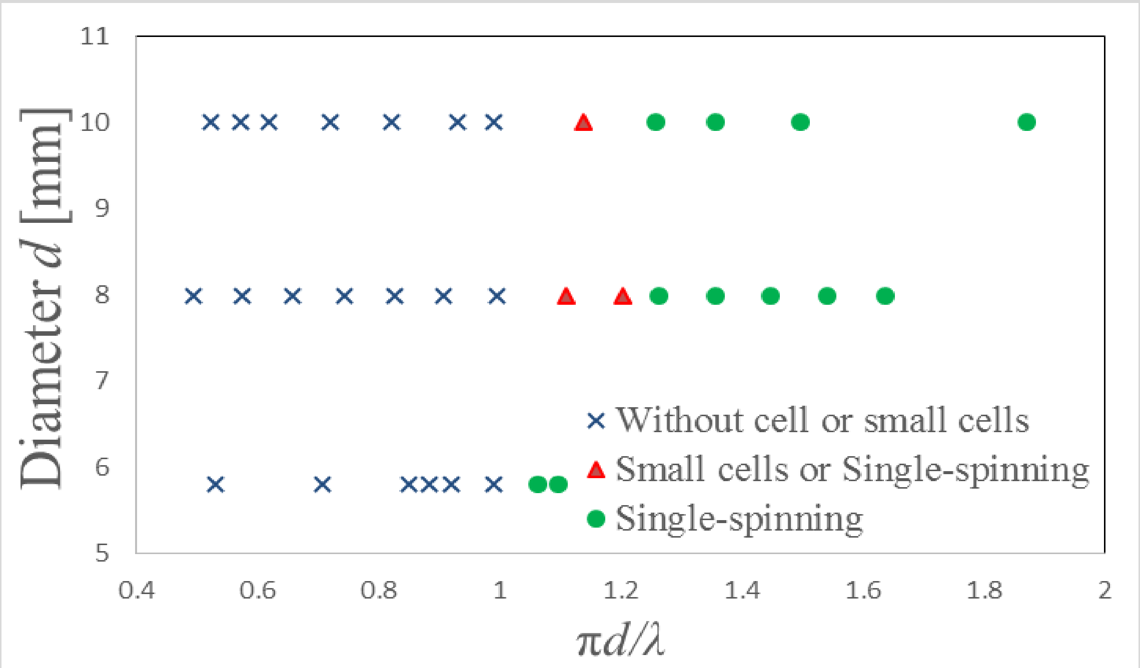

Fig. 7 Propagation mode versus $\pi d/\lambda$ for CASE A, CASE B and CASE C.

3.3 Transition of cellular patterns

We observed the small cells using the long smoked foil. The obtained cellular pattern for tube diameter *d*=10.0 mm and initial pressure P_0=15 kPa (CASE A) is shown in Fig. 8, and for *d*=8 mm and P_0=15 kPa (CASE B) is shown in Figs.9 and 10. The small cells were observed on the beginning of the smoked pattern and the size of cellular patterns gradually increased in Fig. 8. Then the cellular patterns changed from small cells to the single-spinning mode. The single-spinning mode finally disappeared after the track angle changed from 45 deg. to smaller angle. In Fig. 9, the small cells were observed on the beginning of the smoked pattern and the size of cellular patterns gradually increased. This figure is similar to Fig. 8. Then the cellular patterns changed from small cells to the single-spinning mode. The track angle of the single-spinning mode decreased. In Fig.10, the single-spinning mode disappeared. The transition and disappear of cell patterns were observed in both CASE A and B.

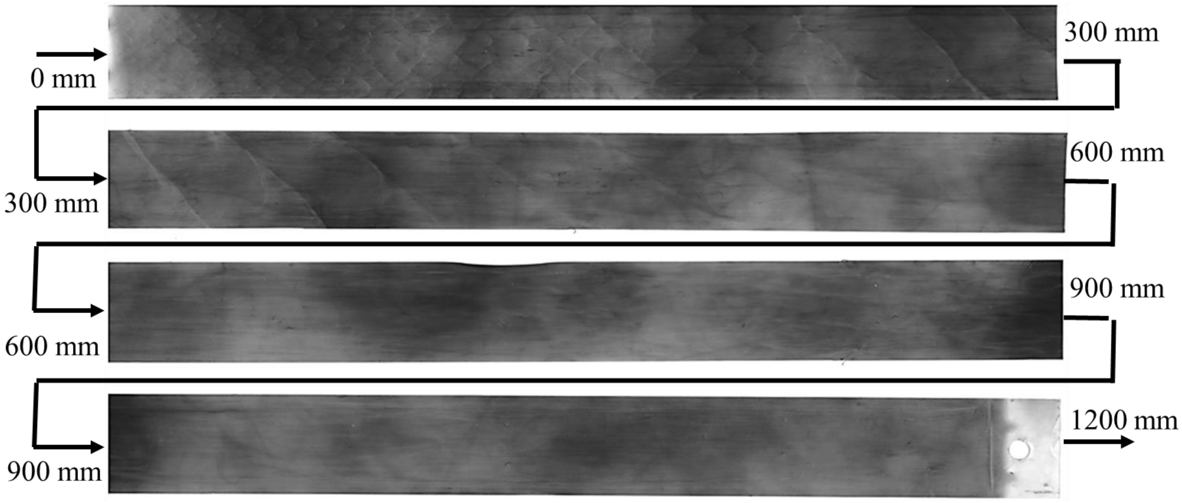

Fig.8 Cellular patterns using long smoked foil for CASE A, P_0=15 kPa

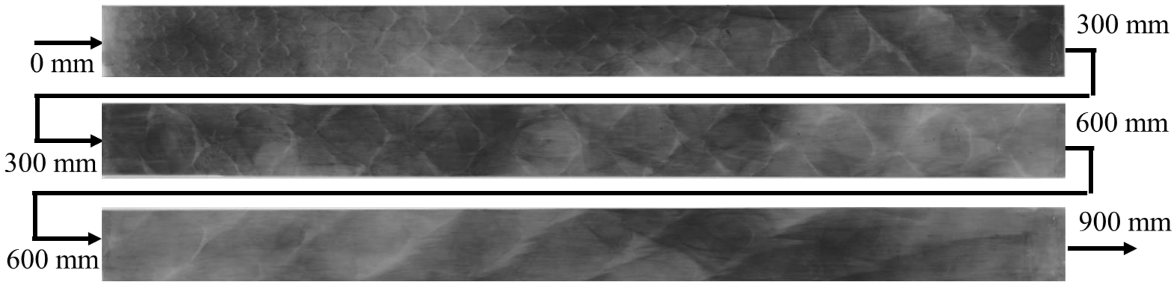

Fig.9 Cellular patterns using long smoked foil for CASE B, P_0=15 kPa.

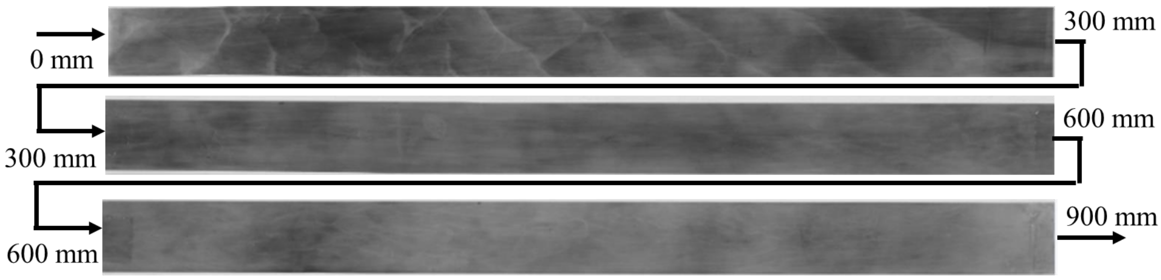

Fig.10 Single-spinning mode disappear for CASE B, P_0=15 kPa.

4 Conclusions

This paper presents an experimental study of Methane/Oxygen detonation near propagation limit in the round tubes with the various diameters. The major conclusions are summarized as follow:

1. Regardless the tube diameter, the detonation velocity is less than the 80 % of C-J velocity as $\pi d/\lambda < 1.0$. As $\pi d/\lambda > 1.0$, the detonation velocity is correspond to the theoretical C-J velocity for CASE A, and is approximately 95 % of C-J velocity for CASE B and C.
2. The existing range of the single-spinning mode is $\pi d/\lambda > 1.0$ and this is independent of the tube diameter.
3. In both CASE A and CASE B, The small cells were observed on the beginning of the smoked pattern and the size of cellular patterns gradually increased. Then the cellular patterns changed from the small cells to the single-spinning mode. The single-spinning mode finally disappeared after the track angle changed from 45 deg. to smaller angle.

Acknowledgements

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