Experimental Study on CH_4/O_2 Detonation Characteristics near Propagation Limit: Influence of Initial Pressure and Equivalence Ratio on Cellular Structure

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1 Introduction

Detonation is a shock-induced combustion wave propagating through a reactive mixture or pure exothermic compound, and has been studied from the safety engineering point of view such as for coal mine explosions or from the scientific point of view of astrophysics as in star explosions. The detailed structures and properties of the detonation have been studied using the experimental and numerical methods as well as through a theoretical approach. Experimental studies have been carried out by many researchers, who provide the useful fundamental and practical data.

Detonations in a circular tube were measured to observe a few modes, for example, spinning, two-headed, and multi-headed modes. Detonations have transverse waves, which move along the circumference and the radius direction. The single spinning detonation has only a transverse wave along the circumference and this 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 detonation is an important issue to predict detonation limits and safety problems because it is the lowest mode of detonation. Therefore, the limit range of the single spinning detonation has to be found numerically as well as experimentally.

Campbell and Woodhead first discovered a spinning detonation in a stoichiometric mixture of carbon monoxide and oxygen in 1926 [1-3]. Bone and co-workers systematically investigated the detonation phenomena to conclude that spin was connected with the mode of coupling between the leading shock front and the reaction zone [4-6]. Mason, Fay and Chu predicted the transverse velocity by the acoustic theory [7-9]. Duff [10], Schott [11], Voitsekhovskii [12, 13], Denisov and Troshin [14] and Huang et al. [15] tried to find the shock structure of the spinning mode and they concluded that the wave front of the spinning mode contains a complex Mach interaction. Topchian et al. [16] investigated the instability of the spinning detonation to divide into three different type: the stable pitch, the periodical unstable pitch, and the pitch covered with a cellular pattern. The effects of the composition of the mixture on spin were described by Gordon [17] and Barthel [18]. Gordon showed the effect of the initial pressure and composition of highly-diluted mixtures of hydrogen and oxygen with a monatomic gas to conclude that the phenomenon of single spin for mixtures close to fuel-lean

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and fuel-rich mixtures was not influenced by the initial pressure of the mixture. Achasov and Penyazkov [19] also investigated the evolution of cellular structure of a gaseous detonation including a spinning detonation in a circular tube as a function of the initial pressure. The transition of cell structure from multi-head mode to single spin mode near the propagation limit of hydrogen/oxygen detonation was reported by Kitano et al [20]. Although there exist many past experimental studies about the spinning detonation, few experimental data about spinning detonation in methane/oxygen gas mixture are obtained.

The purpose of this study is to obtain the existing range of spin detonation and the detonation characteristics by using the soot foiled technique under low-pressure conditions in methane/oxygen gas mixture by changing the initial pressure and equivalence ratio.

2 Experimental Apparatus and Experimental Conditions

Figure 1 shows a 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. The detonation tube is nearly 6 m in length and 10 mm in inner diameter. The premixed sample gas is prepared in the stainless mixing tank. After evacuating the tank by the rotary pump, CH_4 and O_2 gas are introduced into the tank up to 600 Torr and the mixture gas is kept about one day to wait complete mixing of gases by diffusion. Gas purity was 99.9% for CH_4 gas (Kyushu Sanso Corp.) and 99.99995% for O_2 gas (Kyushu Sanso Corp.). The pressure of the gas line was monitored by the capacitance manometer (NAGANO KEIKI Corp.). The thin soot film for recording the soot pattern is prepared spreading soot on it and this was generated using the lamp on the Mylar film 50 μm in thickness which had been cut into a predetermined size in advance.

Before ignition, the soot film is inserted into the glass tube, and the glass tube and the ignition chamber are evacuated for more than 15 minutes to obtain high vacuum for high voltage discharge. Next, the pre-mixed gas is introduced to the glass tube from the mixing tank. After that, we ignite by the spark discharge between the needle electrode using the high-voltage power supply. After the experiment, the soot film inserted into the glass tube is collected as soot pattern, and we checked the cellular structure on the soot film.

According to the above method, we conducted the experiments for initial pressure of P_0 = 50 ~ 250 Torr (5 times in each condition) and equivalence ratio of φ = 0.7, 0.8, and 1.0.

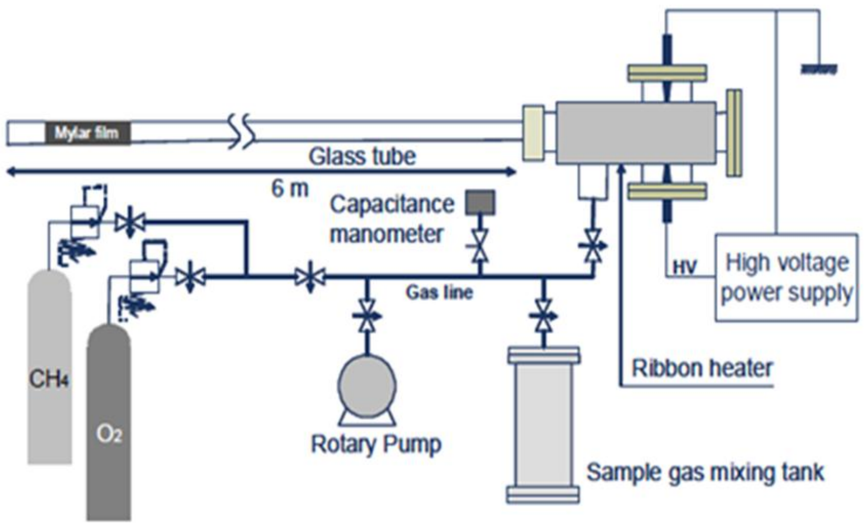

Figure 1. Schematic diagram of experimental apparatus.

3 Results and discussions

Figures 2~4 show the results of the soot patterns obtained by the experiments. The soot films are measured at approximately 4.5 m from the ignition point. Figure 5 shows the classification of the soot patterns for various initial pressures and equivalence ratios. Figure 6 shows the ratio of the induction length to the circumference.

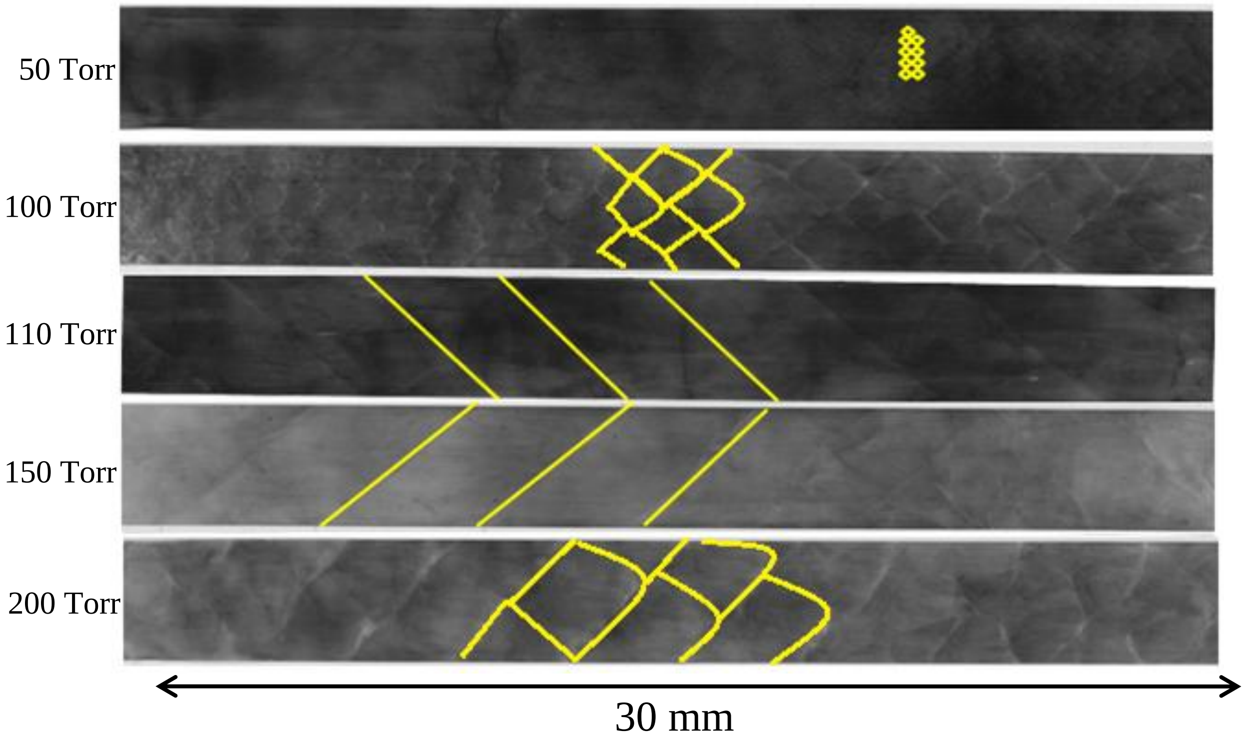

Figure 2. Soot patterns for φ=0.7.

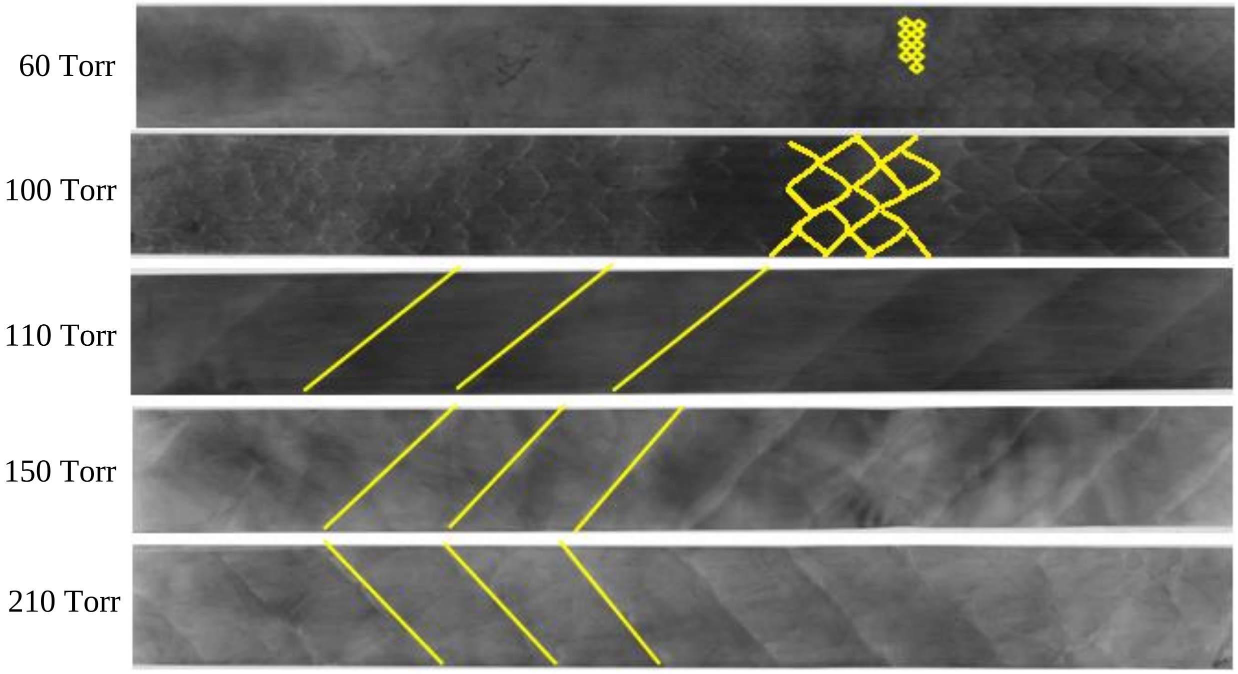

Figure 3. Soot patterns for φ=0.8.

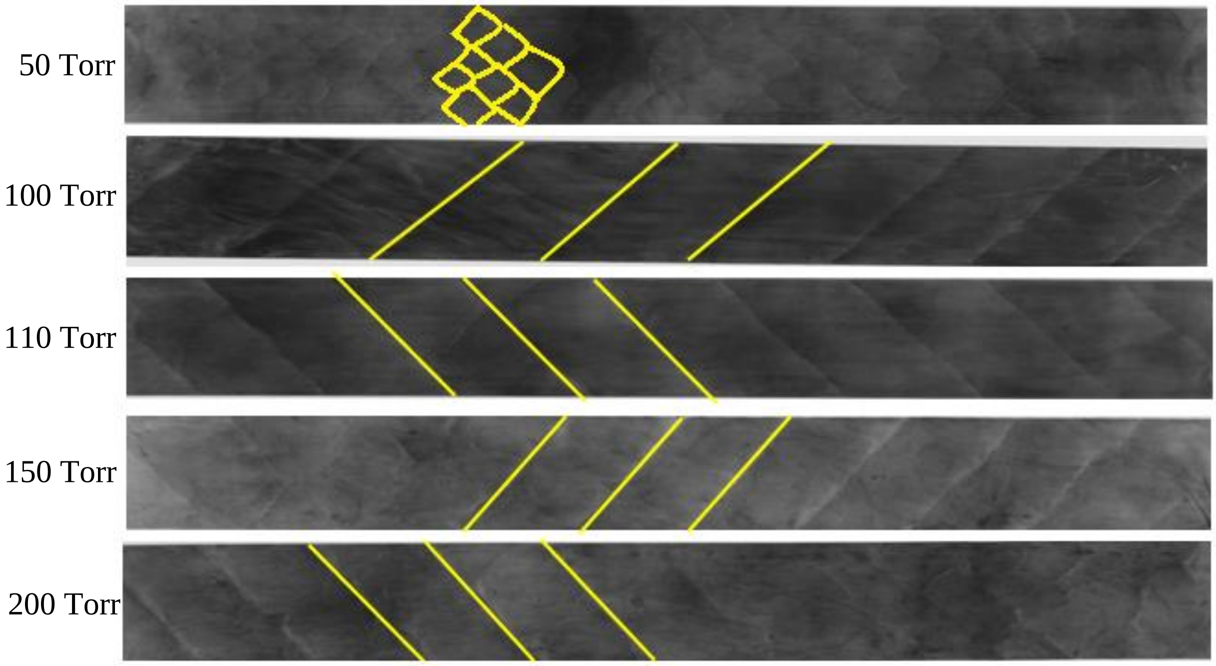

Figure 4. Soot patterns for φ=1.0.

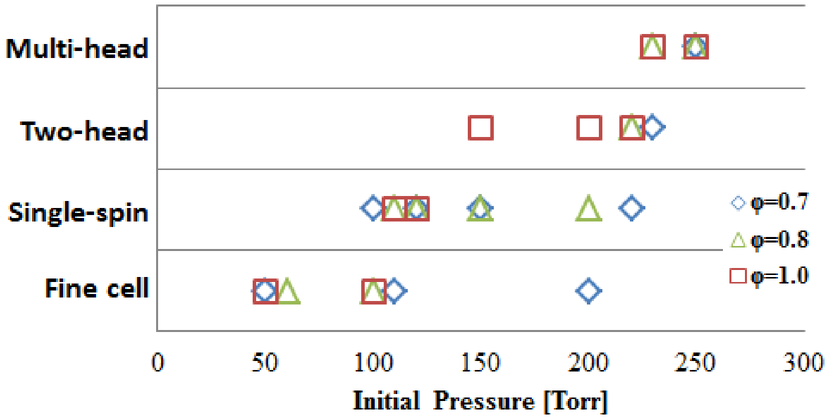

Figure 5. Classification of the soot patterns for various pressures and equivalence ratios.

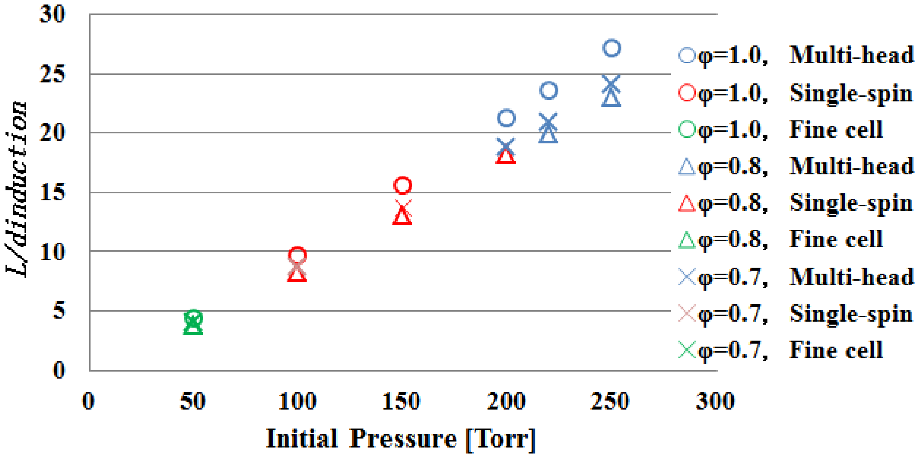

Figure 6. The ratio of the induction length to the circumference.

In the case of all equivalence ratios, the soot patterns were not observed for P_0<50 Torr. From these results, the lowest initial pressure for the detonation limit is approximately 50 Torr. For P_0=110-220 Torr, the soot records showed the typical spiral patterns. These spiral patterns were caused by the spinning detonation which is observed near the propagation limit. The angles of spiral patterns don't depend on the initial pressure except for φ=0.7, and its angle equals 45°. For φ=0.7, the angle was approximately 35° though the theoretical value is 45°. This means that the rotating detonation head along the circumferential direction becomes weak. These soot patterns of the spinning detonation show the different spiral directions. The spiral direction is independent of the initial pressure and equivalence ratio.

The existing region of the spinning detonation and the transitional region between the propagation modes change toward the high pressure region with decreasing the equivalence ratio. In the present experiments, the multi-head mode transits to the single-spin mode at $L/d_{\mathrm{induction}}$ of approximately 20. The spinning detonation was observed at the range of 150~220 Torr for φ=0.7, 110~200 Torr for φ=0.8, and 110~140 Torr for φ=1.0, respectively. This means that the detonation cannot exist under low equivalence ratio.

Throughout this study, though the glass tubes with 1.5 m in length were carefully connected, the soot films inserted in the tubes would generate some disturbance, which affected the detonation mode. Hence, more quantitative experiments are required to evaluate the detonation characteristics, which is insufficient with only the soot foiled technique. We are now planning to research the correlation between the soot patterns and the detonation modes by measuring the propagating velocity used in conjunction with the soot foiled technique, which also can be confirmed the effects of disturbance.

4 Conclusions

The experimental researches were carried out near the detonation propagation limit for CH_4/O_2 gas mixture by changing the initial pressure and equivalence ratio. The soot patterns show some propagation modes depending on the initial pressure. The transition regions of each propagation mode change toward the higher pressure region as the equivalence ratio decreases. The multi-head mode transits to the single-spin mode at $L/d_{induction}$ of approximately 20 in methane/oxygen detonation. The existing range of spinning mode is approximately 150~220 Torr for φ=0.7, 110~200 Torr for φ=0.8, and 110~140 Torr for φ=1.0, respectively. On the soot patterns of the spinning detonations, the angle of spiral patterns is 45° and it does not depend on the initial pressure except for φ=0.7. For the φ=0.7, the angle becomes approximately 35°. This result is a rare case and further research is required in the future.

Acknowledgements

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