Near-limit dynamics of gaseous detonations: Distinguishing tube scale and initial pressure effects

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1. Introduction

Detonation limits - the conditions outside of which a self-sustained detonation wave is unable to propagate - is one of the fundamental dynamic parameters of detonations [1]. As the detonation limit is approached, a variety of unstable, near-limit propagation phenomena occur, e.g., spinning detonations, galloping detonations, and stuttering detonations. Detonation limit conditions can be reached by reducing the initial pressure of the combustible mixture, changing the confinement geometry and/or scale, increasing the amount of an inert diluent, changing the roughness of the confinement boundary.

A number of investigations regarding detonation limits in recent years. Although similar detonation tubes with circular or annular geometries have been normally used, the tube configuration (e.g., tube length, or the ratio between the length and inner diameter L/D) is quantitatively different. Therefore, the critical condition (e.g., p_c - critical pressure) of detonation propagation limit for each apparatus also varies. For example, Wu and Lee [2] reported the maximum initial pressure of $CH_4 + 2O_2$ mixture at which spinning detonations failed was 4.3 kPa, in which they employed a polycarbonate tube of 50.8 mm in diameter and 3 m long. However, a pressure value of 3 kPa was found by Zhang et al. [3] for the same mixture, but with an inner diameter of 36 mm and a length of 2.5 m tube. Generally, the detonation limit is preceded by a detonation velocity deficit. It has been suggested by previous researchers [4, 5] that the mechanism of the velocity deficit is due to the flow divergence by the boundary layer effect in small tubes. Besides, the velocity deficit can also be caused by the effect of heat and momentum losses to the wall [1, 6]. Therefore, it is reasonable to speculate that the critical pressure for self-sustained detonations in tubes with different geometries should also be different. To this end, a universal criterion of detonation limits that considers the tube geometry and initial mixture conditions is desirable.

In this study, detonation experiments were performed in four inner diameter tubes (i.e., D =

36 mm, 25 mm, 20 mm and 13 mm). The detonation cellular patterns and wave velocities were simultaneously recorded at varying initial pressures. In order to examine the results, an alternate length scale is considered. The maximum length of detonation cellular structure (L_{dcs}), defined as the length from the start of the test tube section to the location where no cellular detonation structure is observed, was obtained for each condition to explore the quantitative effects of tube geometry and the thermodynamic properties of the mixture on the detonation limit.

2. Experimental Details

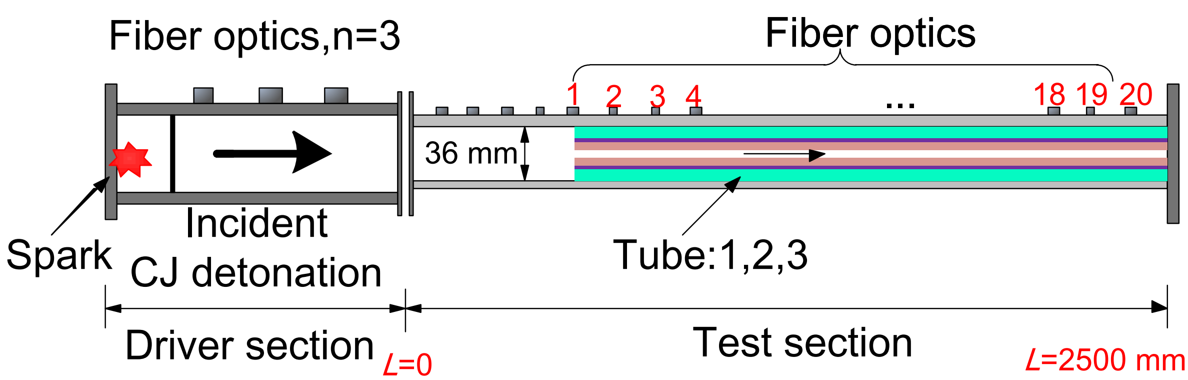

Fig.1 A schematic of the experimental setup

Experiments were conducted in a L = 3700-mm long detonation tube facility. It was divided into a driver section and a test section, which were both separated by a diaphragm (L = 0). The length of the driver section is 1200 mm with an inner diameter of 68 mm, and the test section is 2500-mm long with an inner diameter of 36 mm, as shown schematically in Fig. 1. In the driver section, it was filled with 10 kPa of equi-molar C_2H_2 + O_2; this mixture is very sensitive and readily forms a CJ detonation. The test section was filled with the desired test mixture (CH_4 + $2O_2$). Various transparent acrylic glass tubes with smaller diameter were inserted into the test section, which were used to change the inner diameter of test section. The inner diameters (D) of the tubes (No.1, 2, 3) were 25 mm, 20 mm and 13mm, respectively. The length of all the glass tubes was 2 m (i.e., from L = 500 mm to L = 2500 mm).

In the experiment, smoked foil technique was used to record the structure of the detonation wave. Clear Mylar sheets with the thickness of 0.1 mm were uniformly covered with soot using a kerosene lamp. To obtain records of the detonation structure in the test section, the Mylar sheet was placed along the internal face of tube (typically L = 500 mm - 2500 mm).

In addition, the combustion wave velocity was also determined to observe the attenuation of the detonation propagation. The local wave velocity was obtained by calculating the distance over two neighboring signals from optical fibers. Optical fibers connected to a photodiode (IF-95OC) were used to record the time-of-arrival (TOA) of the combustion wave. Three optical fibers with an interval distance of 20 cm were located in the driver section to verify if a CJ detonation was indeed formed before transmitting into the test section. In the test section, 24 optical fibers with an interval distance of 10 cm were used to measure the TOA. Figure 1 shows

20 optical fibers from L = 500 mm to 2500 mm, and 4 more fibers were placed before L = 500 mm.

3. Results and discussions

3.1 Maximum length of detonation cellular structure (L_{dcs})

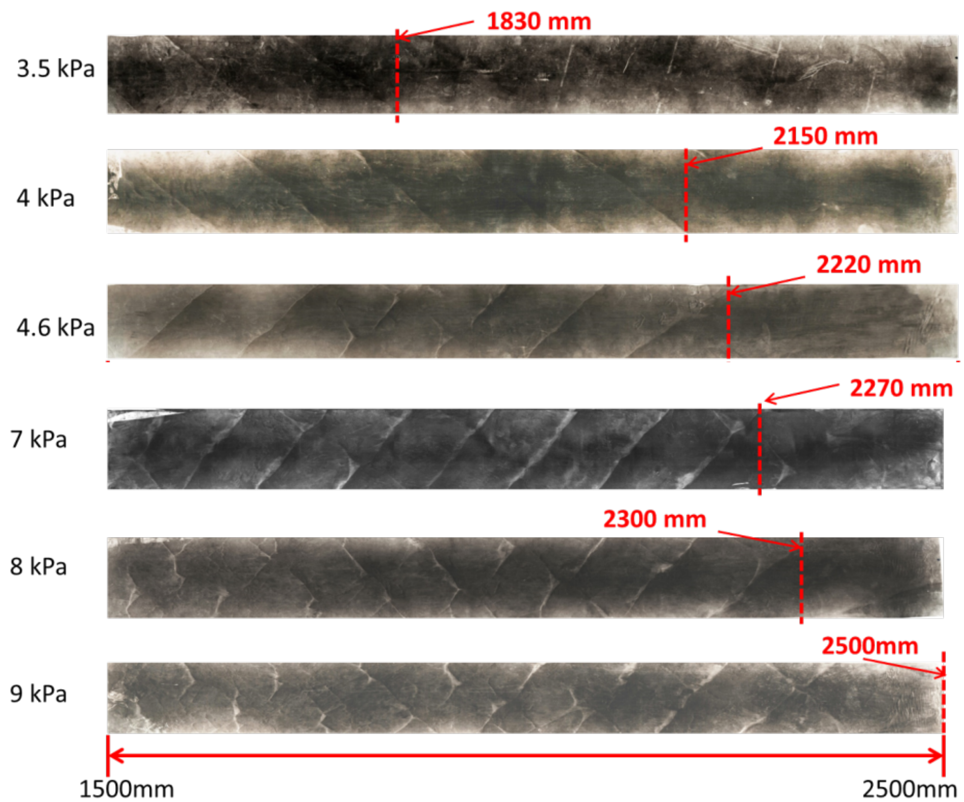

Fig. 2 Detonation cellular pattern in the D = 36 mm tube with the variation of initial pressure

Figure 2 shows the results of L_{dcs} for the $CH_4 + 2O_2$ mixture in a 36-mm inner diameter circular tube at different initial pressures. At p_0 = 3.5 kPa, the detonation structure first appears as a single-headed spin, which is the typical phenomenon as the detonation is approaching its limit. For this case, L_{dcs} = 1830 mm, after which no cellular structure can be found. The latter indicates that the leading shock decouples from the following reaction zone and hence, the detonation failure occurs.

3.2 Scaling analysis of detonation failure behavior

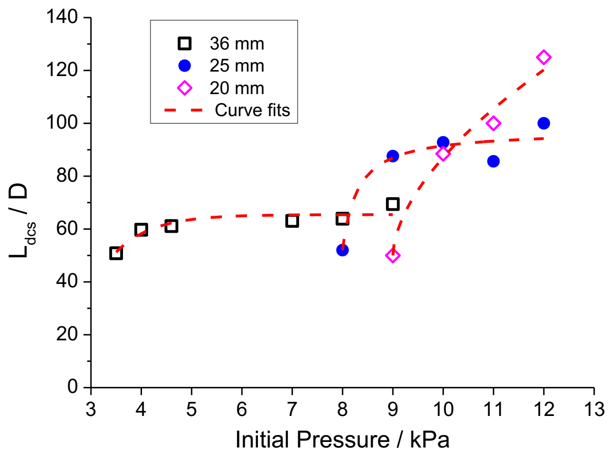

Fig. 3 L_{dcs}/D as a function of initial pressure in tubes

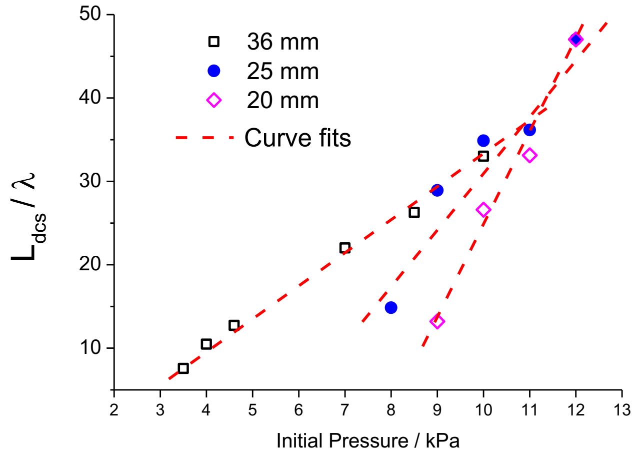

Fig. 4 Variation of L_{dcs}/λ with the initial pressure

When a detonation propagates in a tube, besides the thermodynamic properties of the mixture, the propagation behavior is greatly dependent on the boundary condition. The relationship between the detonation propagation behavior and the initial pressure in different diameter tubes is given by Fig. 3. For the D = 13 mm case, galloping behavior is observed, i.e., after the disappearance of the spinning detonation, the deflagration can eventually re-initiate and form an over-driven detonation again after a certain distance of propagation. The criterion that is used to estimate the L_{dcs} in larger diameter is thus not suitable for the D = 13 mm case and hence, only D = 36 mm, 25 mm and 20 mm results are considered for discussion in Fig. 3. For the D = 36 mm circular tube, as the initial pressure increases from 3.5 kPa to 9 kPa, the value of the ratio between L_{dcs} and tube inner diameter (D) slowly goes up. In other words, the detonation propagation is not sensitive to the initial pressure in the larger inner diameter tube (D = 36 mm). In the middle-size diameter circular tube, i.e., D = 25 mm, it is clear that L_{dcs}/D increases with the increase of initial pressure, which indicates a small variation of the initial pressure may cause a long distance for either successful propagation or failure of a detonation. Finally, for the D = 20 mm diameter tube, the value of L_{dcs}/D increases very abruptly with increasing initial pressure, indicating L_{dcs}/D has a strong dependence on its initial pressure.

Figure 4 shows the variation of L_{dcs}/λ with the initial pressure for different tubes. In this study, the detonation cell sizes data are taken from Zhang et al. [7]. In Fig. 4, it is found that a linear relationship between L_{dcs}/λ and p_0 for a specific tube can be obtained. The increase of L_{dcs}/λ is however more abrupt in the smaller diameter tube, which confirms again the propagation of detonation is more dependent on the initial pressure in smaller diameter tube.

4. Conclusions

In this study, the near-limit dynamic behavior of detonation propagation and failure was investigated experimentally. Simultaneous smoked foils and velocity measurement were used to observe the evolution of the detonation cellular structure and velocity deficits, from which limits (i.e., critical pressures) were defined. An alternate characteristic length (L_{dcs}), defined as the length from the start of the test tube section to the location where no cellular detonation structure, is recorded with varying initial pressure in four different inner diameter tubes, i.e., D = 36 mm, 25 mm, 20 mm and 13 mm. The quantitative relation between the cellular detonation propagation distance, the tube geometry, and the thermodynamic properties of the mixture were explored. The results show that L_{dcs} generally decreases with decreasing mixture initial pressure, and it decreases faster in smaller diameter tubes.

By scaling L_{dcs} with tube inner diameter (D) and detonation cell size (λ), it is found that the decrease of L_{dcs}/D and L_{dcs}/λ are more abrupt in smaller diameter tubes with decreasing initial pressure. It thus suggests that the detonation propagation dynamics is more sensitive to the initial pressure in the smaller diameter tube. The latter is explained based on the argument of the significant boundary layer displacement thickness growth at low initial pressure and the curvature due to the lateral mass divergence. The distribution rate of global curvature over the whole detonation front due to the boundary layer effect is faster in smaller tube and thus it leads to a more abrupt decrease sensitive to initial pressure.

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