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# Cellular Property of the Detonation Wave of Pre-mixed Methane-Oxygen in Annular Tube

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**Abstract:** In order to investigate the detonation propagation in the annular tube, the experiments are conducted with methane-oxygen mixture. Annual tubes with different inner diameter $D_0$ were configured and smoked foils were fixed on both outer wall and the inner wall of the annular tube to record the detonation structure. Firstly, it is found that transverse wave modes on both outer wall and the inner wall of the annular tube increase with increasing initial pressure and inner diameter of the channel. In addition, the measurement of angle between the transverse wave and the tube axis disagrees acoustic theory within the error range. In the results, the angle and the cell size changes less with pressure and more with different position of the channel, demonstrating the strongly dependence of the tube geometric. What's more, the trajectories of right-running transverse wave were traced and some of the transverse waves disappeared in the polycarbonate tube, because the initial energy of different transverse waves are different and the energy required to sustain the transverse vibration of spinning detonation must be derived from the chemical energy release at the front.

**Key words:** cellular structure; methane-oxygen mixtures; detonation wave; annular tube; smoked foil

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Methane is the main component of natural gas, biogas and gas of coal seam. It can be used as a material for a variety fuels and is widely used in civil and industrial applications due to the property of high combustion heat value and clean combustion productions[1-3]. However, the mixture of methane and air has the danger of burning and exploding in the environment of heat source and open flames. In recent years, many fire and explosion which caused extremely serious injuries and property damage occurred frequently due to the out of control of flammable gases. Therefore, it is necessary to study the formation and development mechanism in order to prevent or reduce the damage caused by detonation and achieve the purpose of preventing severe explosion disasters[4-6].

Although the inner structure of spinning detonation recorded by the detonation experiment seems a little result recorded on the tube wall at the same time are an orderly fish-scale pattern. What 's more, the cellular size given by many scholars after this was obtained by this fish-scale pattern[7-9].

Schott[10] established a resin-glass model to show the three-dimensional structure of spinning detonation. Bykovskii et al.[11-12] first proposed the transverse wave motion of single-headed, double-headed and four-headed spinning detonation. It was found that a left-handed transverse wave and a right-handed transverse wave were showed in the smoked foil in the double-headed spinning model, forming rhombus long the tube

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wall. While two left-handed and right-handed transverse waves observed in the smoke foil in the four-headed spinning model, forming two rhombuses around the tube. Teng Honghui[13] studied left-running (LRTW) and right-running (RRTW) transverse waves in numerical simulations. The results showed that high activation energy and low wedge angle were favorable for left-handed transverse waves, while right-handed transverse waves were related to activation energy, wedge angle, and left-handed transverse wave. Many scholars stated that the stability of rotation based on the experimental pressure results obtained by detonation experiments with multiple fuels in combustion chambers of different sizes and shapes.

The cell structure, studied by researchers who used various methods, is an important parameter reflecting the characteristics of detonation waves[14-16]. Scott I Jackson et al.[17] studied the changes in the cell structure of unstable premixed gas. Based on previous studies, Zhang Bo et al.[18] measured the detonation cellular size of $CH_4$-$H_2$-$O_2$ and gave a cellular size prediction formula based on a chemical kinetic mode. Hoi Dick Ng et al.[14] analyzed the experimental results of $C_2H_6O$-$O_2$ and provided a basis for analyzing the detonation risk of $C_2H_6O$ in combination with chemical kinetic sensitive behavior. Wu Yuwen et al.[19] studied the stability of rotary detonation of several premixed gases. Based on the algorithm of Shepherd et al.[20], Lee et al.[21] carried out digital processing of trajectory pictures, but the conclusion was not systematic and comprehensive. Zhao Huanjuan et al.[22] studied the experimental results of spinning detonation of $CH_4$-$O_2$ premixed gas, and used the method of digital experimental results to analyze the cell structure of $CH_4$ -$O_2$ premixed gas.

Although many previous studies have been performed regarding the detonation propagation in the tube, detonation propagation in the porous-walled tubes, the detonation wave structure information contained in the given experimental records was very limited in the existing research results, and the internal structure of the detonation wave needs deeply study[23-25]. In the present work, $CH_4$-$O_2$ is selected as the test mixture. The reasons are that on one hand, methane has significant applications in the chemical industry, and the detonation hazard of methane deserves sufficient attention. On the other hand, $CH_4$-$2O_2$ is considered a typical unstable mixture[26-28], for which the transverse waves are extremely strong, and the detonation cellular pattern has a highly irregular feature. This paper focus on the analysis of the cellular structure in the annular tube under the condition of different inner diameters and different pressures, and the continuty of detonation wave in the annular tube was also studied.

## 1 Experimental Details

In the present study, pre-mixed methane-oxygen were used as test mixtures. Experiments were performed in a 1.0 m long, 80 mm inner diameter steel driver section followed by a test section of steel detonation tube with 1 m in length and inner diameters of 60 mm, 40 mm and 20 mm respectively, which is shown in Fig. 1a. The annular channel test section was created by inserting smaller diameter tubes supported by fins into the end of the detonation tube, which thickness was 5 mm. The detonation cellular structure were recorded by a 1m-long smoked foil which was placed on the outer wall of the annular tube, the inner wall of the annular tube and in the polycarbonate tube.

Under a series of initial pressure conditions, detonation experiments on an annular tube with an inner diameter of 60 mm were conducted, and performed the same operation in 40 mm and 20 mm tubes. As shown in Fig. 1b, the detonation wave results could be obtained from the smoked foil in the experiment. The first picture represented the experimental results of the inner wall of the outer tube, indicated by a green line; the second was the outer wall of the inner tube,

indicated by a pink line; and the third was the inner wall of the inner tube, indicated by a blue line. In order to make the detonation wave results clearer, the experimental pictures were processed using photoshop to obtain the results shown in Fig. 1c.

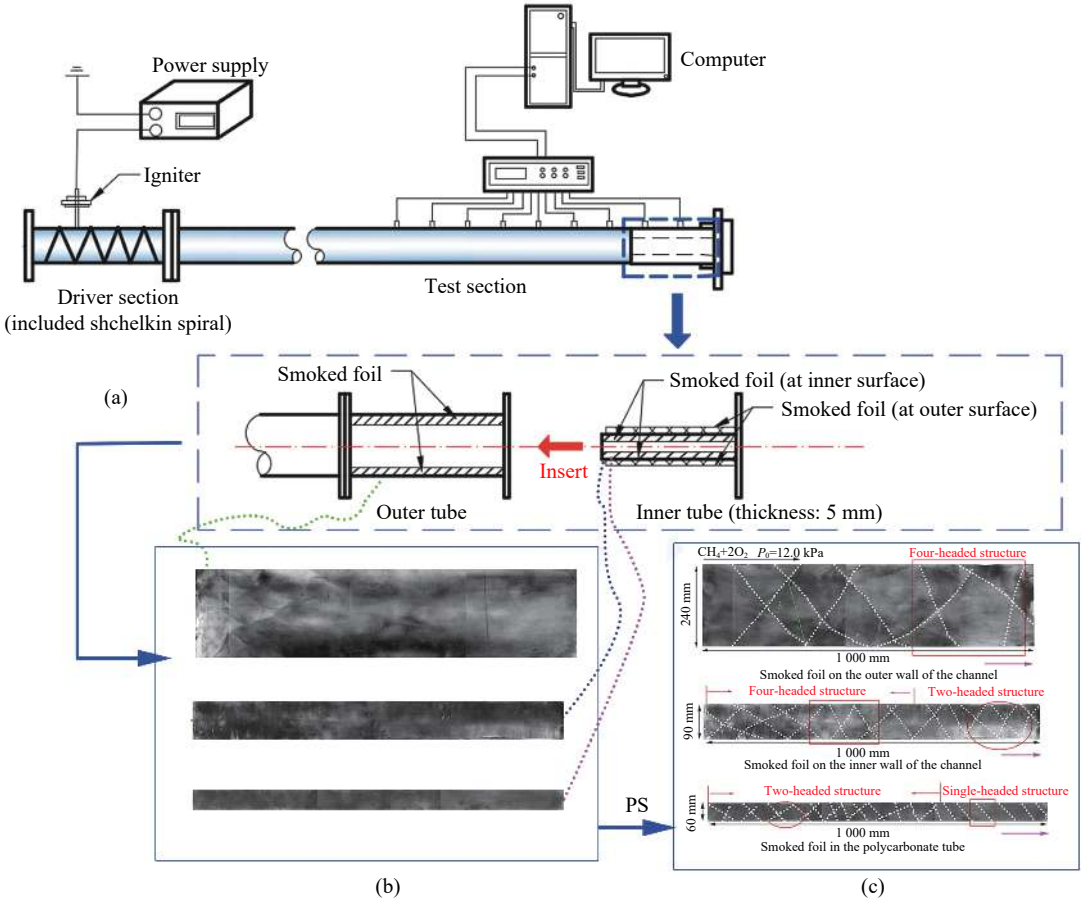


Fig. 1 Sketch of the experimental set up: (a) Experiment system; (b) Smoked foil record; (c) Triple point trajectory depiction

## 2 Results and Discussions

The detonation wave was unstable and had a complicated three-dimensional cellular structure. This structure was composed of an incident shock wave, Mach stem, and transverse wave[29]. In order to describe the flow field structure of spinning detonation in detail, the circular pipe was often expanded to obtain a cross-sectional view. Fig. 2 shows the two-dimensional steady flow field structure of the spinning detonation. The flow field was divided into four areas, I was the unburned area before the detonation wave, II was the detonation product area, III was the detonation product area after the detonation wave, and IV was the detonation products compressed by oblique shock wave. Among them, there were discontinuities in contact between areas I and II, and areas III and IV. At the same time, the position of the detonation wave was marked in the following figures. In this paper, the internal structure of the spinning detonation of the methane-oxygen premixed gas in the annular tube were explored through the analysis of the cellular structure of the expanded cross section.

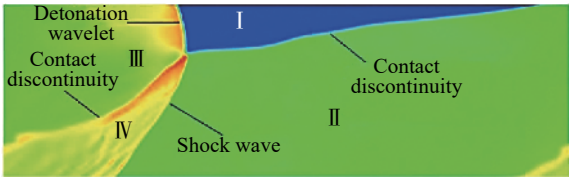


Fig. 2 Two-dimensional steady flow field structure of the spinning detonation[30]

It was of great significance to describe the propagation of detonation waves in the tube by constructing the trajectory of the shear wave. In this experiment, the smoked foil surrounding the wall of the tube recorded the trajectory of the triple points. A spinning detonation where a single Mach configuration at the wall rotates circumferentially is, in general, particular to a round tube. For a single headed spin, only one spinning trail was recorded on the smoked foil on the side wall. Away from the limits, the spin frequency increased as higher acoustic modes were excited, and the detonation structure changes from single-headed spin to multi-headed spin. High-frequency spinning detonations were generally referred to as multiheaded detonations, also known as cellular detonation. For the double-headed spin, the pattern on smoked foil consisted of a left-handed and a right-handed transverse wave trajectory, giving a single diamond across the width of the tube circumference. There was transverse wave in each spinning direction. The four-headed spin pattern corresponded to two transverse waves in each direction, forming two diamonds around the tube. The six-headed spinning had three transverse waves in each direction, giving three diamonds across the width of the tube circumference.

The $CH_4$-$2O_2$ mixtures was an unstable gas. In fact, experiments have been carried out on multiple sets of detonation wave structures under different pressures. In this paper, the results of $P_0$=12.0 kPa and $P_0$=13.0 kPa under non-extreme conditions are selected for display and analysis. In addition, Zhao et al.[22,31] found that when the unstable gas was the $CH_4$-$2O_2$ mixtures, the ultimate pressure of detonation was $P_0$=5.0 kPa, and the stable double-headed spinning detonation structure was formed in the circular tube with a diameter of 80 mm under the initial pressure of 12.0 kPa. Based on this conclusion, the characteristic of detonation with methane-oxygen mixture under 12.0 kPa and 13.0 kPa was analyzed. It was impossible to install the smoked foil on the outer wall of the channel and the inner wall of the channel at the same time for the tube with inner diameter of 60 mm ($D_0$=60 mm) due to the too narrow channel. Therefore, the smoked foil was only installed on the inner of the external tube and the inner of internal tube for $D_0$=60 mm. The experimental results were shown in Figs. 3–8.

The structure of the detonation wave was very unstable due to the unstable property of $CH_4$-$2O_2$ mixture. In this paper, the white trajectory was used to trace the cellular structure in order to facilitate the reader to clearly read the structure of the detonation wave. The direction of detonation wave propagation was indicated by the pink arrow, and the number of transverse waves of the spinning detonation was shown in the red box. It was found that the structure was very irregular and changed along the propagation. The transverse wave modes of the inner of external tube were larger than that on the outer wall of internal tube, and the outer wall of internal tube was larger than that in the inner wall of internal tube under the same conditions. What 's more, when the diameter of the inner tube or the initial pressure increased, the number of transverse wave in the tube increased significantly. The characters of spinning detonation was dependent on the tube diameter and the initial pressure.

Nevertheless, Fig. 5 and Fig. 7 showed that there was not more observable number of transverse waves when increasing the inner tube diameter or increasing the initial pressure. The reason may be that the frequency of transverse was high when it was away from the limits, and the corresponding cell size in the detonation front became small compared to the characteristic dimensions of the tube and was no longer controlled by the tube geometry. Thus, in the cases of $P_0$= 12.0 kPa, $D_0$=60 mm and $P_0$=13.0 kPa, $D_0$=40 mm, the cell size was too big to fit in the tube.

The higher transverse acoustic mode was aroused when the detonation was far away from

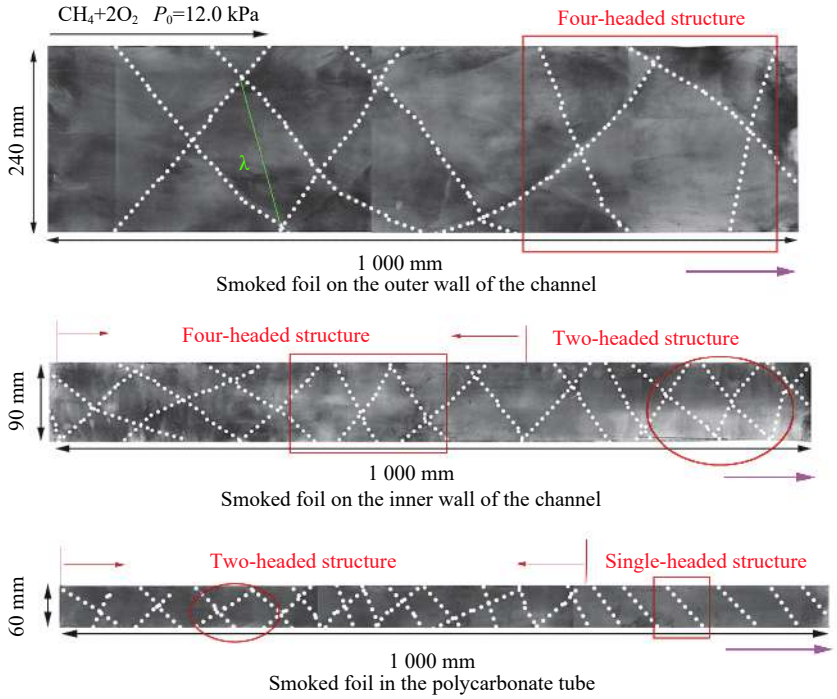


Fig. 3 Records for internal tube with diameter of 20 mm under 12.0 kPa

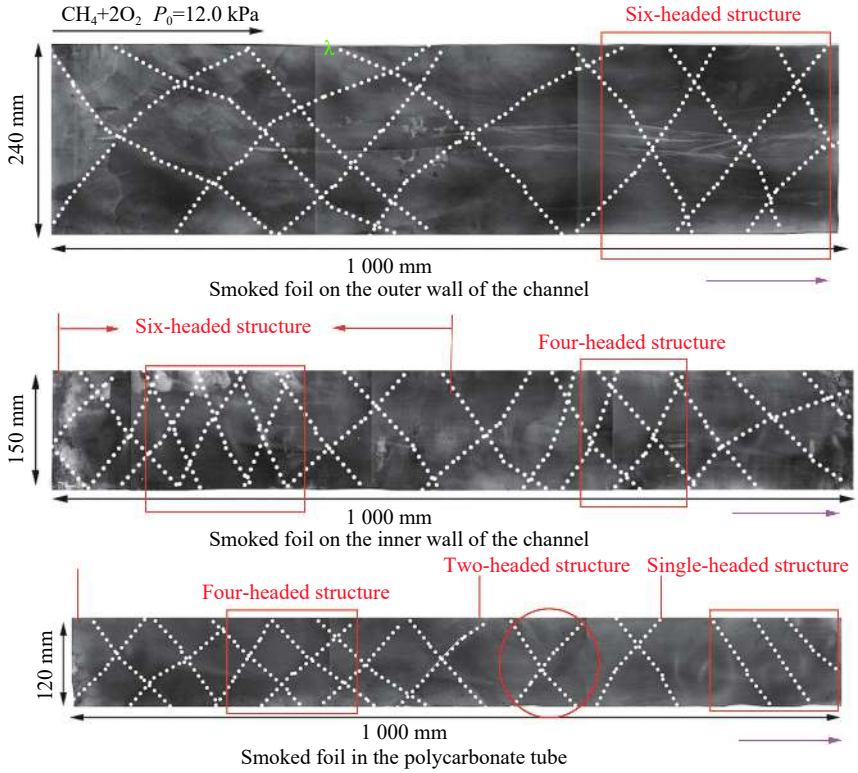


Fig. 4 Smoked foils record for inner tube with diameter of 40 mm under 12.0 kPa

the limit, and the frequency of spinning detonation could be described by analyzing the transverse acoustic oscillation in the gas column after detonation. Due to the performance of methane-oxygen premixed gas was unstable, the measured $\alpha$ was compared with $\alpha_e$, which was calculated in the acoustic. The results were shown in Fig. 9, and the formula provided by acoustic the-

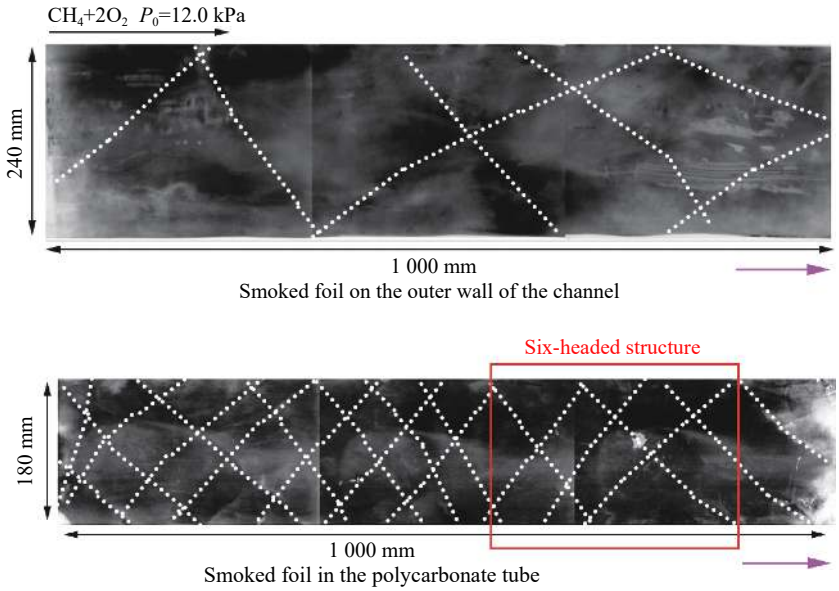


Fig. 5 Smoked foils record for inner tube with diameter of 60 mm under 12.0 kPa

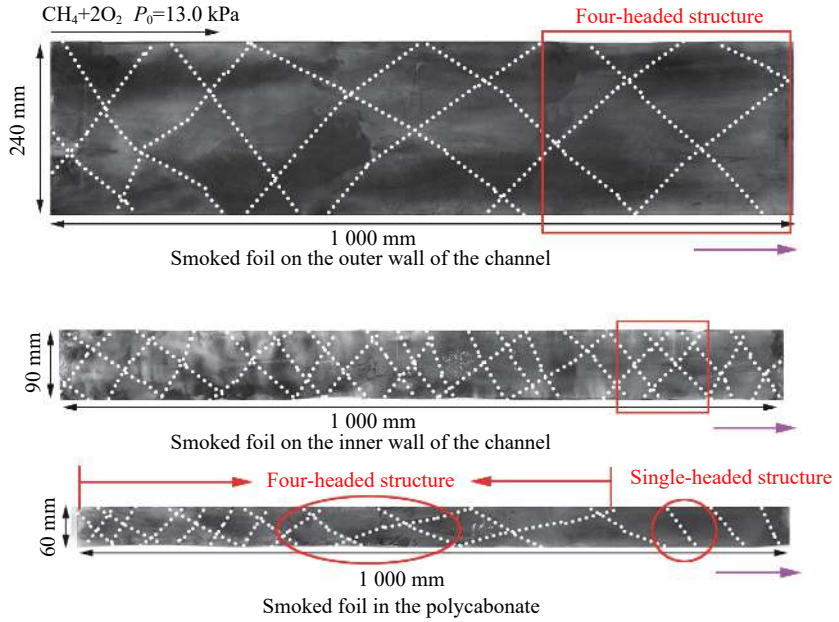


Fig. 6 Smoked foils record for inner tube with diameter of 20 mm under 13.0 kPa

ory was used in the calculation

$$\tan\alpha = \frac{\pi d}{p_n} = \left(\frac{k_{nm}R}{n}\right)\left(\frac{c_1}{D}\right) \qquad (1)$$

where $\frac{c_1}{D} = \frac{\gamma}{\gamma+1}$, $n$ was the number of circumferential modes, $m$ was the number of radial modes, $k_{nm}R$ could be found from the Bessal function, and $\gamma$ was the specific heat ratio.

It was interesting to find that the $\alpha$ and $\alpha_e$ in the inner wall of inner tube fitted better within the error range (45–30°). However, comparing the $\alpha$ with $\alpha_e$ measured in the outer wall of the outer tube and the inner wall of the inner tube, it was found that there was a relatively large error between the measured value and the theoretical value. This result proved that the existing theoretical theory of detonation acoustics was not applicable in an annular tube. Perhaps it was effective to start with the derivation of the theoretical formula of the acoustics by changing the as-

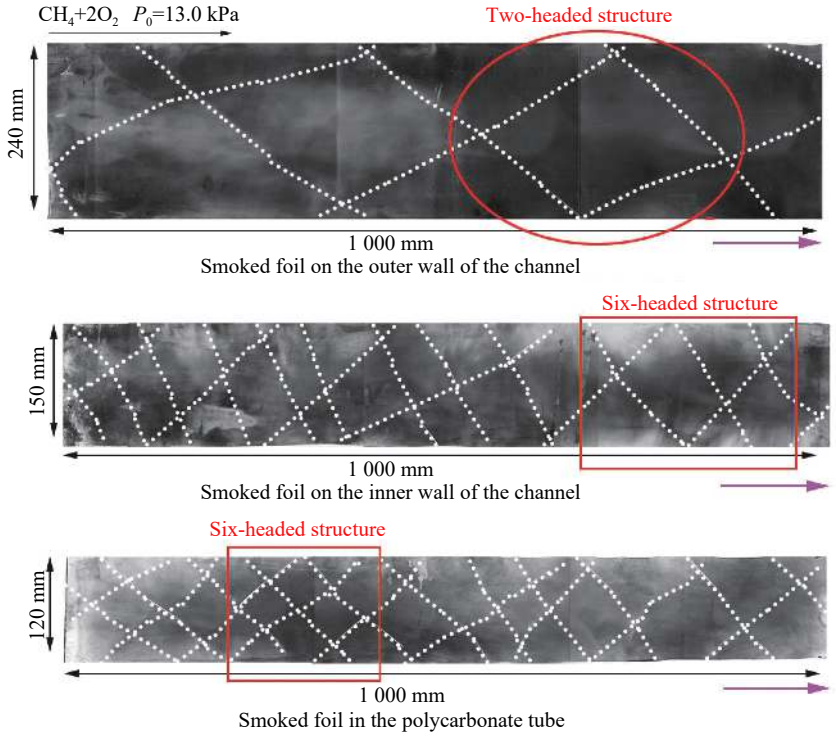


Fig. 7 Smoked foils record for inner tube with diameter of 40 mm under 13.0 kPa

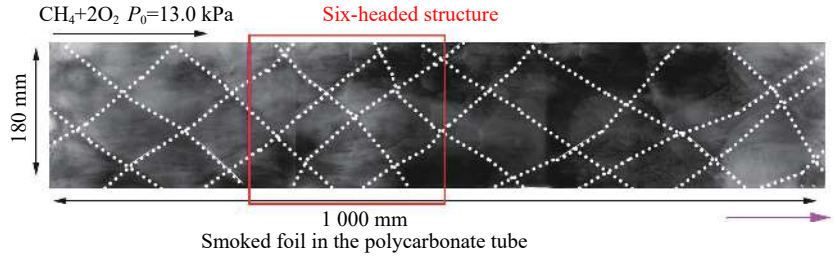


Fig. 8 Smoked foils record for inner tube with diameter of 60 mm under 13.0 kPa

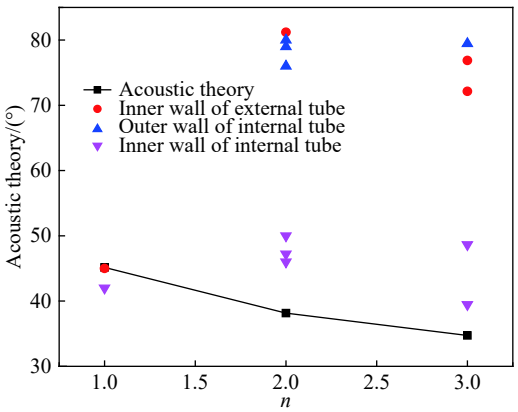


Fig. 9 Comparison between measured and calculated values of $\alpha$ from acoustic theory

sumption of a single wall condition and considering the influence of the bilateral value condition, then the theoretical formula in the annular channel would be obtained.

The cell boundaries were defined by the intersection of an ensemble of transverse waves with the leading shock front. The transverse waves were sustained by the nonuniform energy release at the detonation front. As shown in Fig. 2, cell size ($\lambda$) that characterize was given prominence with the green line. In this paper, a line across the tube's cross-section was drawn, the intersections of the cell boundaries with the line was counted, and the length of the line was divided by the number of intersections to obtain the average cell dimension. The results of the cell size is shown in Fig. 10, it could be seen that the cell size of the inner wall of external tube was

much larger than that of the outer wall of the internal tube and inner wall of the internal tube. As the initial pressure increased from 12.0 kPa to 13.0 kPa, there was just slight changes for the cell size, demonstrating the spinning detonation was strongly dependent on the diameter of the tube. This conclusion agreed well with the acoustic results (Fig. 10).

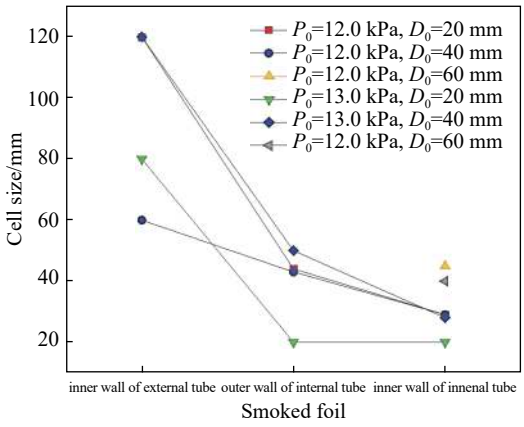


Fig. 10 Spacing of transverse waves from walls

Trajectories with an angle between 0° and 90° from the propagation direction were called "right-running transverse wave" (RRTW) and those between –90° and 0° were called "left-running transverse wave" (LRTW). Teng et al.[13] found that high activation energy and small angle (low overdrive) were beneficial to the LRTW formation. However, more complex trends were observed in the RRTW formation, and different variations existed depending on the range of activation energy. Maybe the reason for that was the influencing factors of LRTW and RRTW were different. Figs. 2–7 showed that there was decoupling phenomenon during the detonation propagation, and the propagation distance of LRTW was greater than that of RRTW. The LRTW did not completely disappear within the length of the tube, while the RRTW disappeared under different conditions.

The trajectories of RRTW under different conditions were depicted with photoshop, as shown in Fig. 11. The blue square was used to mark the propagation trajectory of the same transverse wave, which had the longest propagation distance. Red vertical lines were used to show the position of the longest distance of the transverse wave. It was found that part of transverse wave, which disappeared during the propagation process could only be seen in the inner wall of external tube and the outer wall of internal tube, and did not appear on the polycarbonate tube. Actually, the energy required to sustain the transverse vibration of spinning detonation must be derived from the chemical energy release at the front, and the rotation of the transverse pressure wave was driven directly by the energy released at the spinning head at the front. Hence, the reason may be that the transverse vibration energy was insufficient, which caused some transverse waves to be unable to propagate into the polycarbonate tube. At the same time, the propagation of the transverse waves could not be maintained because of the lack of initial activation energy.

In some cases, detonation decoupled at different position along the polycarbonate tube, and the furthest distance where the decoupling occurs varied with the different initial pressure and the tube diameter. The research results showed that the triple point trajectory of detonation disappeared when it propagated in the inner tube. Moreover, the smaller the size of the inner tube, the more unstable the explosion wave and the shorter the distance for decoupling. The results of Fig. 12 showed that the propagation distance of RRTW increased as the initial pressure increased under the same diameter of the inner tube of the annular tube. And under the same initial pressure, the propagation distance of RRTW also increased as the diameter of the inner tube increased. While when the initial pressure was 13.0 kPa and the inner diameter of the tube was 40 mm, there was no decoupling occurred in the tube. The results also demonstrated that the propagation were more dependent on the diameter than the pressure.

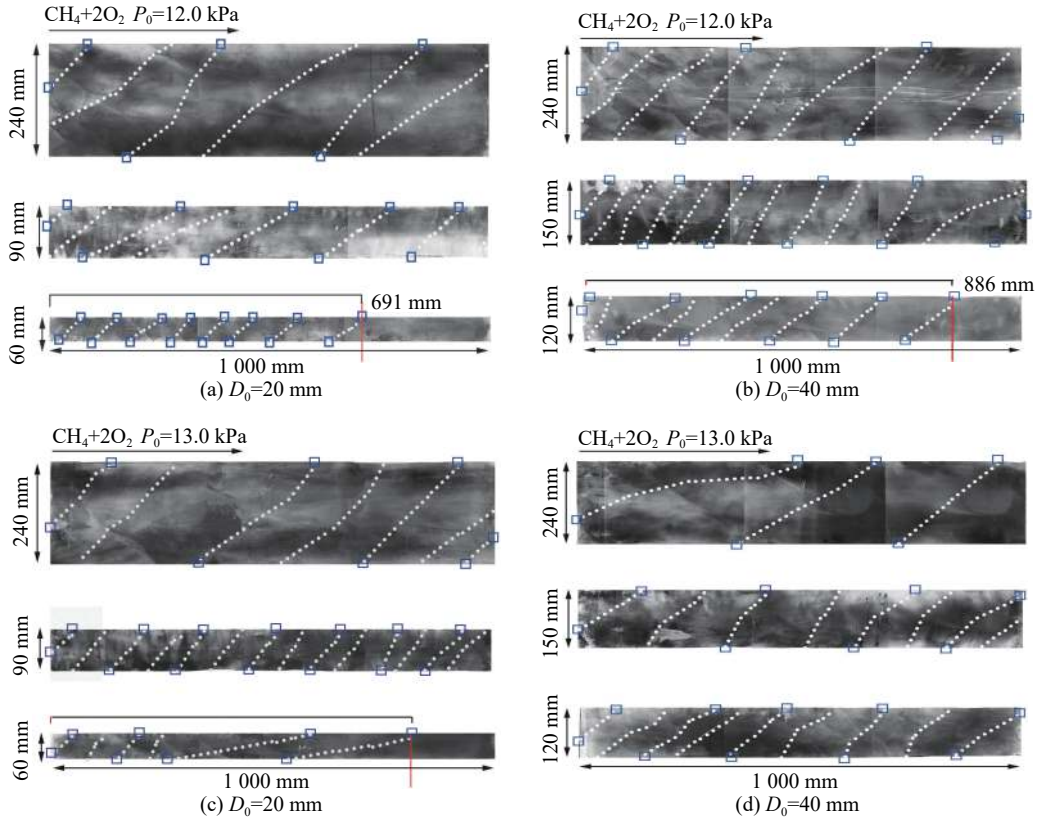


Fig. 11 Smoked foil of RRTW

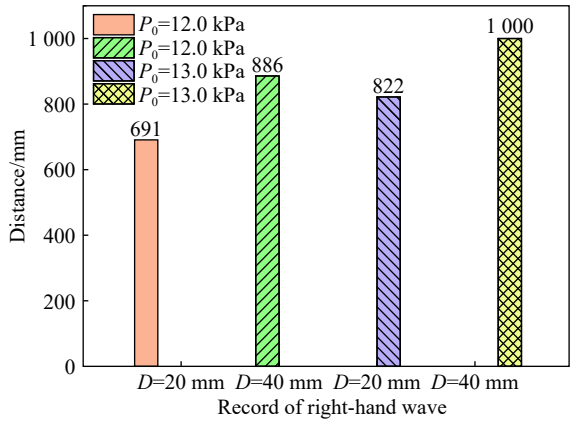


Fig. 12 Propagation distance of RRTW

## 3 Conclusions

The cellular structure of spinning detonation of $CH_4$-$2O_2$ in annular tubes have been analyzed. The following conclusions can be drawn:

① Under $P_0$=12.0 kPa and $P_0$=13.0 kPa, the cellular structure was measured by smoke film in the annular tubes whose the inner diameters are 20 mm, 40 mm, and 60 mm, respectively. The transverse wave trajectory of $CH_4$-$2O_2$ is recorded and depicted. The transverse wave modes increase with increasing the initial pressure and the inner diameter of the tube. Nevertheless, the observable transverse wave modes for the inner wall of external tube decrease when the inner diameter is increased. Meanwhile, in the cases of $P_0$=12.0 kPa, $D_0$=60 mm and $P_0$=13.0 kPa, $D_0$=40 mm, the cell size are too big to fit in the tube. The reason may be that when away from the limits, the frequency of the transverse is high, and the corresponding cell size in the detonation front became small compared to the characteristic dimensions of the tube and the tube geometry no longer controlled the cell size.

② The existing detonation acoustic theory is not perfectly suitable to the annular tube. Under the experimental conditions, the results obtained by the formula calculated from the inner wall of the inner tube have a small error range, which is consistent with acoustic theory. The acoustic theoretical value in the channel has a large error and does not conform to the existing formula. It is considered to get proper a result by changing a

single boundary condition.

③ Part of the detonation wave appear on the inner wall of external tube, the outer wall of internal tube and the inner wall of internal tube, while others can be only observed on the inner wall of external tube and the outer wall of internal tube. This is because the initial energy of different transverse waves are different, and the energy required to sustain the transverse vibration of spinning detonation must be derived from the chemical energy release at the front. Additionally, the decoupling of the detonation was observed by the smoked foil records, because of the disappearance of RRTW. It is found that the detonation wave of $CH_4$+2$O_2$ mixtures disappeared when the propagated in the straight pipe. The smaller the tube size, the more unstable the detonation wave, the easier it is to decouple detonation waves. On the other hand, the results suggest that in our experimental conditions, the tube diameter is dominant in detonation propagation than the initial pressure, also, spinning detonation is dependent strongly on the tube diameter.

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