Detonation cellular structure of CH_4-O_2 mixture in annular channel

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Abstract： In order to study on the cellular structure of spinning detonation, experiments were carried out in annular channels. The limit of detonation was measured as well as the detonation cellular structure was recorded under different pressure. Smoked foils were used in the experiments. They were fixed at the inner-wall and outer-wall of the plastic tube, and the inner wall of the steel tube. Another, round and annular smoked foils were fixed at the end of the plastic tube and the gap between the plastic tube and the steel tube respectively. The results show there are continuous trajectory along the big steel tube to the small plastic tube. Another, the cell size on outer-wall of the channel is larger than that on the inner-wall of the channel. Meanwhile, the cell size becomes smaller when the detonation goes into the inner tube. The change of the cellular structure is for the detonation self-maintain. Compared with records in 20 mm, 40 mm and 60 mm, the cell size decreases with the tube diameter decreasing. The boundary condition is important role in for the cellular structure. The compression by the tube wall on the detonation cannot be ignored.

Keywords Detonation structure, Annular channel, CH_4-O_2, cell size

1 Introduction

After nearly a hundred years of development, the technology of gas turbine and turbofan engine based on constant pressure combustion mode has been very mature and perfect. It has become very difficult to improve substantially the propulsion thermal efficiency of these machines. Detonation has higher thermal efficiency than normal combustion [1].

Different from deflagration, detonation is another way for the energy transformation. In detonation, chemical reaction is initialized by the shock wave, and the speed is larger than the sonic velocity. After the detonation wave, the pressure and temperature increase rapidly with strong chemical reaction. Many studies show that the exothermic process of detonation is similar to that of constant volume combustion, and is much higher than that of deflagration. Detonation is one of the ways to improve the performance of the propulsion system. At the same time, it is important to research the cellular structure of detonation. The three-dimensional internal flow field structure of rotating detonation is analyzed by calculation [2]. Three-dimensional numerical simulation of continuous rotating detonation engine was carried out to obtain the flow field structure of detonation wave initiation and its steady propagation. The radial change of flow field in combustion chamber and thrust performance of engine were analyzed, and the propagation characteristics of two-phase detonation wave were revealed [3].

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Because of energy constraints, saving energy in thermodynamic systems is one of the most important things.Forced convection plume reflection superposition is a process to improve the heat transfer rate of heat system, which includes many active and passive methods. The annular tube design enhances reflection overlay. The forced convection is realized, and a new boundary layer is formed on the inner pipe wall, which enhances the convection.

The effect of the curvature of the inner and outer wall on detonation wave is calculated by using the elementary element reaction model [4]. The steady propagation of continuous rotating detonation without inner column is calculated with Euler equation in cylindrical coordinate system [5-7]. Aspden et al [8] calculated the three-dimensional structure of detonation of methane. More experiments are needed to research the cellular structure. The purpose is to study the real three-dimensional triple point trajectories of detonation waves. In this paper, smoked foils were used to record the transverse waves on the wall of the tubes and the cross section.

2 Experimental details

2.1 Annular channels configuration and the mixture

In the experiments, a polycarbonate tube was inserted into a steel tube to configure the annular channel as Fig 1. The diameter of the steel tube is 80 mm. In this study, we use three types of the polycarbonate tube whose diameter is 20 mm, 40 mm and 60 mm respectively. All of them are 5-mm thick. So that the width of the annular channel is 50 mm, 30 mm and 10 mm respectively. In addition, Methane-oxygen in stoichiometric was used in these experiments, the mixture was put in a 40 L tank for at least 24 h for the homogeneity.

2.2 Smoked foils

The smoked foils were used to record the cellular structure in the channel and in the polycarbonate tube. As the pick and blue dashed rectangle in Fig 1, for the channel, the smoked foils were set on both the outer wall and the inner wall of the channel. Along the detonation propagation, the transverse waves spin and sweep the smoked foils on both side. In addition, in order to record the detonation structures on the cross section, an annular smoked foil was set on the end section of the annular channel. Similarly, in the inner tube, a smoked foil was set in the polycarbonate tube. On the end section of the polycarbonate tube, an end-on smoked foil was set on, too.

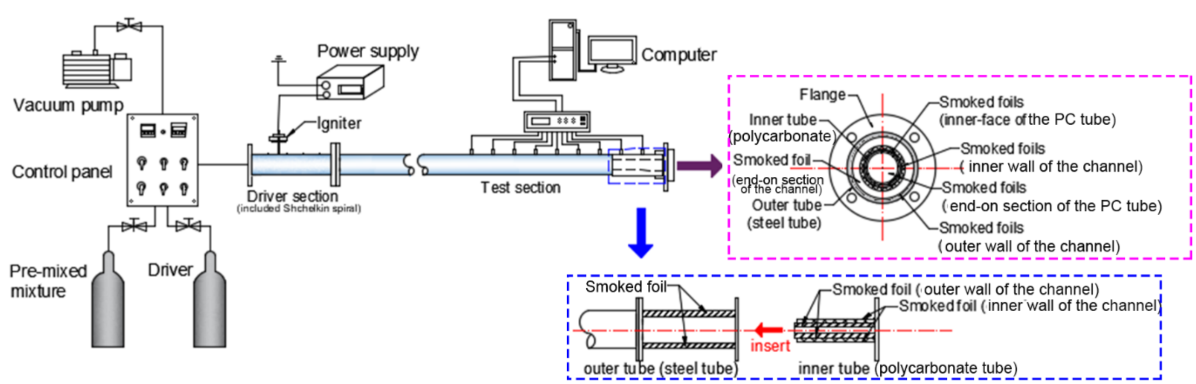

Fig 1. Sketch of the apparatus

3 Experimental results

3.1 Smoked foil records

Firstly, the experiments in the tube with inner diameter of 80mm were finished. The velocity results and smoked foils records shown that the limit is around 4 kPa. Signify results are shown as below.

Tube | End-on smoked foil records

steel tube

20mm plastic tube

40mm plastic tube

60mm plastic tube

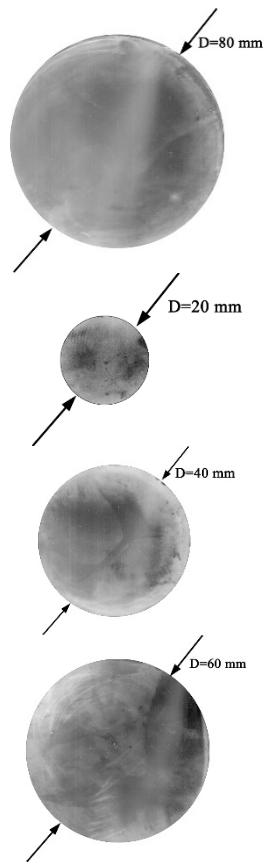

Figure 2. Smoked foils on the steel tubes

The inner detonation structure can be drawn according to the 60 mm plastic tube end on record in Fig 2. Signify structures are finished as shown in Fig 3.

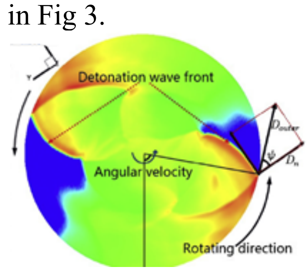

Figure 3. Detonation structure on cross section

The smoke foil in the configuration channel is shown in Figure 4. The trajectory of the transverse wave on the smoked foil is indicated by yellow dashed lines. The upper part is recorded on the outer wall of the channel. The middle is the record on the inner wall of the channel. Meanwhile, in Fig. 4, the annular end-on smoked foil on the right side records the transverse wave trajectory on the cross section of the channel. In general, the transverse wave propagates along the tube axis along the detonation, sweeping the smoked foil on both sides of the channel. Therefore, the homologous trajectory is recorded on two smoked foils. In Figure 3. The pink ring refers to the point on the edge of two smoked foils that propagates the same distance along the detonation. These points and corresponding trajectories are generated by the same transverse wave behavior. However, not all points have the same distance on the edge.

The edge points of the two smoked foils at the end of the channel and the walls of the channel should be homologous. In Fig. 3, blue points a1 and a1, a2 and a2, green points b1 and b1, b2 and b2 are homogeneous points. Meanwhile, in Fig. 3, the transverse wave spin direction is indicated by a cyan arrow. Below 12 kPa, double head detonation occurs in the annular channel. One transverse wave rotates clockwise (A1-B1) and the other rotates counterclockwise (A2-B2). In addition, the bottom of Figure 3 shows the polycarbonate tube and the smoked foil at the end-to-end portion. Below 12 kPa, a single head detonation occurs in a 20 mm polycabonate tube. This is different from a double ended tube in the channel because the tube diameter is smaller than the channel width.

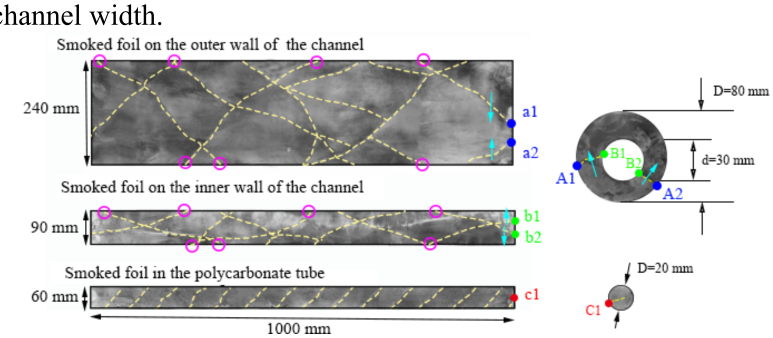

Figure 4. Smoked foils record for 50 mm channel

In addition, under 13 kPa, the smoked foils on the inner wall and outer wall were shown in the Fig 5. It is noted that the trajectories pattern on the outer wall decay from double-headed into single-headed structure along the propagation. However, the trajectories pattern on the inner wall shows the detonation is double-headed one. Meanwhile, there are two trajectories of the transverse waves on the annular smoked foil. But one of them, trajectory B1-, cannot extend into the other side of the annular channel. It agrees with the smoked foils record. The transverse wave decays or even fails near the outer tube wall along the propagation. The reason is that the activated molecules collide with the tube wall and weakens the detonation reaction. The larger curvature on the outer wall causes larger energy consumption on outer wall than on the inner wall of the channel. The transverse wave behaviour is different on the two walls of the annular channel, and the big curvature and width of the channel can be the mainly responsible for this phenomenon.

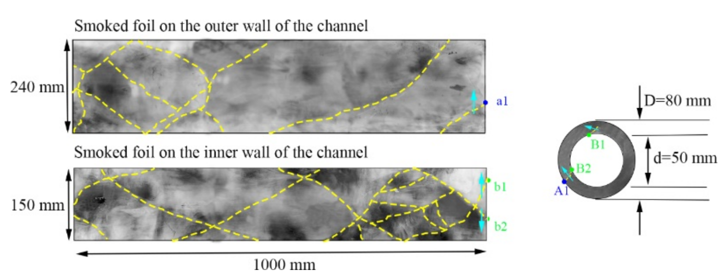

Fig 5. Smoked foils record in 30 mm channel

3.2 Cell size

The detonation is divided into two parts due to the insertion of the inner tube. One propagates through the channel and the other propagates through the inner tube. The transverse waves in the channel and inner tube will sweep across the smoked foil and leave a trajectory on it. The cell size of the inner surface of the inner tube is shown in Fig 6. The detonation of methane-oxygen mixture in chemometrics is strongly unstable and the cell structure is very irregular. In Figure 6, the cell size decreases as the initial pressure increases. The results obtained by the database [9] and Jesuthasan [10] are also plotted in Figure 6 for comparison.

As shown in Figure 1, the smoked foil is also placed on both sides of the channel. The cell size on different smoked foils is shown in Figure 7. The cell size decreases as the initial pressure increases. The cell size of the outer wall is larger than the cell size of the inner wall. The result of the polycarbonate tube is also shown in Figure 7, which is the smallest of the three.

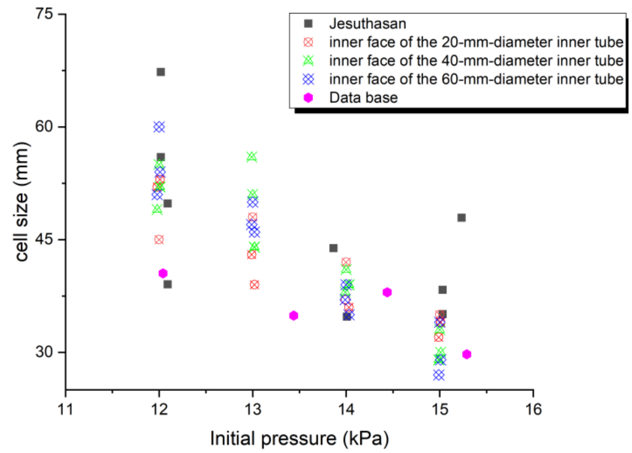

Fig 6. Cell size in the polycarbonate tube

The boundary layer effect has an important influence on the cell structure. Detonation is affected by the momentum loosening and boundary layer effects of the outer and inner walls. Due to the negative displacement effect of the boundary layer, the streamline will diverge toward the reaction zone [11]. The energy consumption of the tube walls reduces the intensity of the transverse wave. At the same time, the curvature of the two channel walls are different. The diffusion of mass into the boundary layer weakens the reaction and affects the transverse wave structure. Larger circumferences and larger curvatures are associated with more energy consumption. This explains that not all points on the sides of the two smoked foils are at the same distance during propagation.

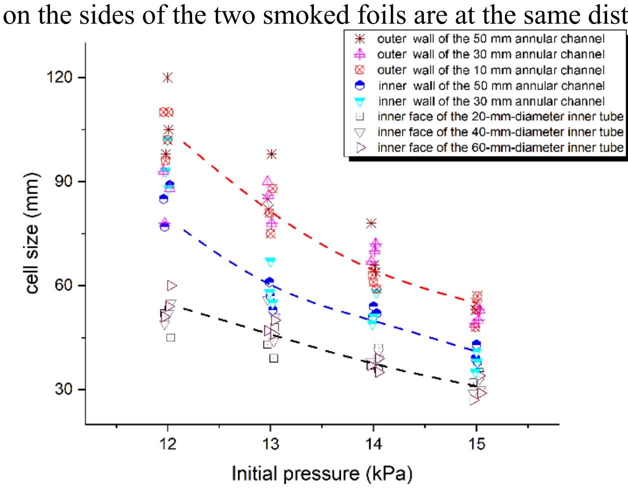

Fig 7. Cell size on the two walls of the channel, and in the polycarbonate tube

4 Conclusions

An experimental study about the detonation structure of methane-oxygen in the annular channels unfold the effect of big channel width on the detonation structure. The conclusion are presented as following:

(1) Compared with the smoked foil records on the outer wall and inner wall of the annular channel, it can illustrate the transverse wave collision and emergence while it spinning around the tube axis along the detonation propagation. Generally, the detonation can maintain steady propagation in the channels.

(2) The big curvature and width of the channel has influence on the detonation structure and cause the difference on the structure on the two walls of the channel. The cell size on the outer wall is larger than that on the inner wall because of the boundary layer effect and the large curvature of the channel.

(3) Because the transverse waves collisions and the strong unstable detonation, the structure on the inner wall and outer wall can be different in the channel. The transverse wave decays in the channel along the propagation.

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