Propagation Mechanism of quasi-Detonation in Annularly Rough tube

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1 Introduction

Combustible gas is widely used in the fields of petrochemical, mining, gas supply and etc. The investigation of propagation of detonation waves in rough tubes is considerably significant on explosion prevention and suppression. The propagation of so-called quasi-detonation in orifice plates-filled tubes has been studied previously [1-7]. It is found that the local phenomena of the interaction between the detonation and the orifice plates dominates the propagation, i.e. diffraction through the orifice opening followed by a re-initiation upon reflection on the tube wall. There have also been numerous studies on the effect of orifice plates on the deflagration to detonation transition (DDT) [7-11]. However, these studies do not directly relate to the present study where the mechanism of detonation propagation in rough tube with spirals is investigated. For the Shchelkin spiral, especially with small wire diameter and small pitch, there is an averaged or continuous effect of the spiral producing "roughness" on the propagation of the detonation [12]. However, the orifice plates give a "discrete" effect on wave propagation via disturbance created by reflection waves. Only in previous studies [12-13], it is indicated that in rough tubes with spirals, detonation velocity can vary continuously from close to the theoretical Chapman-Jouguet (C-J) value far from the limits to about 0.4 V_{CJ} where the detonation fails. It is also found that detonation propagation is facilitated in rough walled tubes, which means the detonation limit is extended, even though wall roughness results in a decrease in velocity. As the detonation approaches the limits in the rough-walled tube, the detonation shows a single-headed spinning structure. Below the minimum initial pressure that causes the occurrence of the single-headed spinning phenomena, detonation fails and decays to deflagration.

In the previous studies [12-13], the spiral was inserted into the tube to provide roughness. The smoked foils were inserted into the inner diameter of the spiral near the end of the tube to record the quasi-detonation structures. However, the smoked foils, by this way, can only capture a short length of the detonation structure because the detonation front adjust itself fast when entering into a smooth "tube" formed by a smoked foil. To avoid this problem, an annularly rough tube can be used with the smoked foil stuck on the smooth inner surface to capture a long length of the frontal structures of the quasi detonation wave. Thus, in the present study, the roughness created by the spiral was used to analyze the basic transform mechanism

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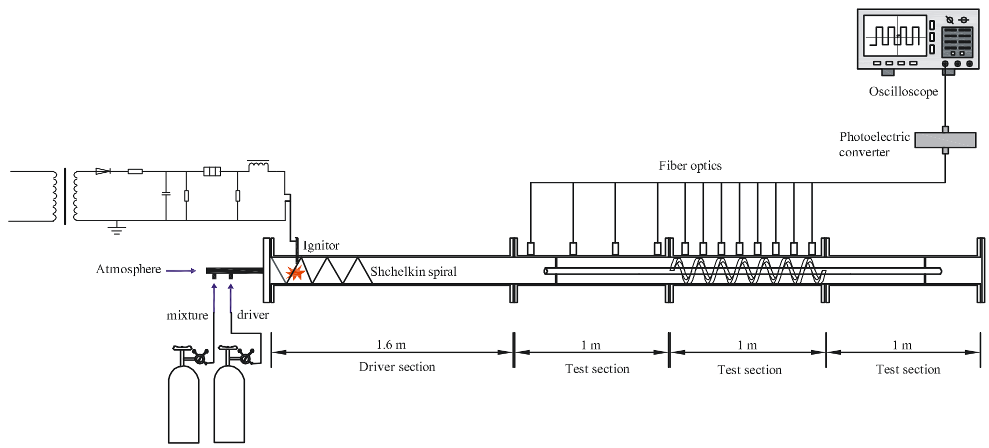
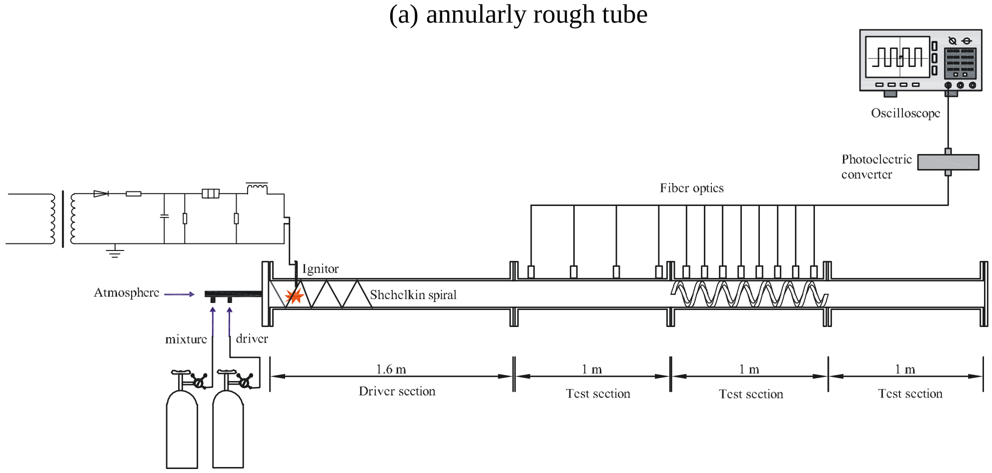
as a simplified simulation. The detonation propagation and limit in an annularly rough tube are studied to provide insight into the physics. The results in the case of circularly rough tube are also provided as a comparison.

2 Experimental details

The detonation tube used in the present study consists of a 1.6 m long steel driver tube of a diameter of 88 mm followed by a polycarbonate tube of a diameter of 88 mm and of a length of 3 m connected by an aluminum flange. The detonation is initiated in the driver tube by a high energy spark. A short length of Shchelkin spiral was also inserted downstream the spark plug to promote the formation of a self-sustained C-J detonation. The annular tube is created by inserting a smaller diameter aluminum tube (30 mm) into the core of the polycarbonate tube. A schematic of the experimental apparatus is shown in Fig. 1(a). Fig. 1(b) shows the difference between annularly rough tube and circularly rough tube: a smaller diameter aluminum tube providing the annular form doesn't exist in circularly rough tube.



(a) annularly rough tube



(b) circularly rough tube

Fig.1 Experimental apparatus

To generate wall roughness, Shchelkin spirals with rectangular cross section of various wire lengths and a pitch of one tube diameter were used. Previous investigations indicated that a pitch about one tube diameter is the most effective roughness [10]. The diameters of the wire of the spiral used were δ=10, 14 and 20 mm for the 88 mm tube. The ratio of the wire diameter to the tube diameter δ/D was used to characterize the wall roughness of the Shchelkin spiral. The spiral characteristics are shown in Fig. 2. A mixture of C_2H_2+2.5O_2+xAr is used and the choice include those mixtures considered as "stable'' with regular cellular pattern and ''unstable'' with highly irregular cell pattern.

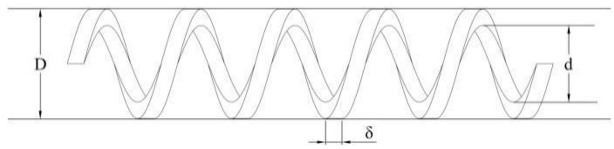


Fig.2 Dimensions of the spiral (D- tube diameter, d- see-through diameter, δ- wire length)

In the present study of detonation propagation in an annular rough tube, the primary diagnostic is velocity measurement using photodiodes. Photodiodes record the time of arrival of the detonation wave along the tube which allows for a detonation trajectory to be obtained. The slope of the detonation trajectory corresponds to the velocity of the detonation. It is possible to determine if a steady detonation wave is obtained in the annularly rough tube via photodiode records. In general, it is found that the detonation adjust to the wall roughness rapidly upon entering the annularly rough tube. A long length of smoked foil was stuck to the smaller tube near the end of the tube to record the cellular structure of the detonation front.

3 Results and Discussions

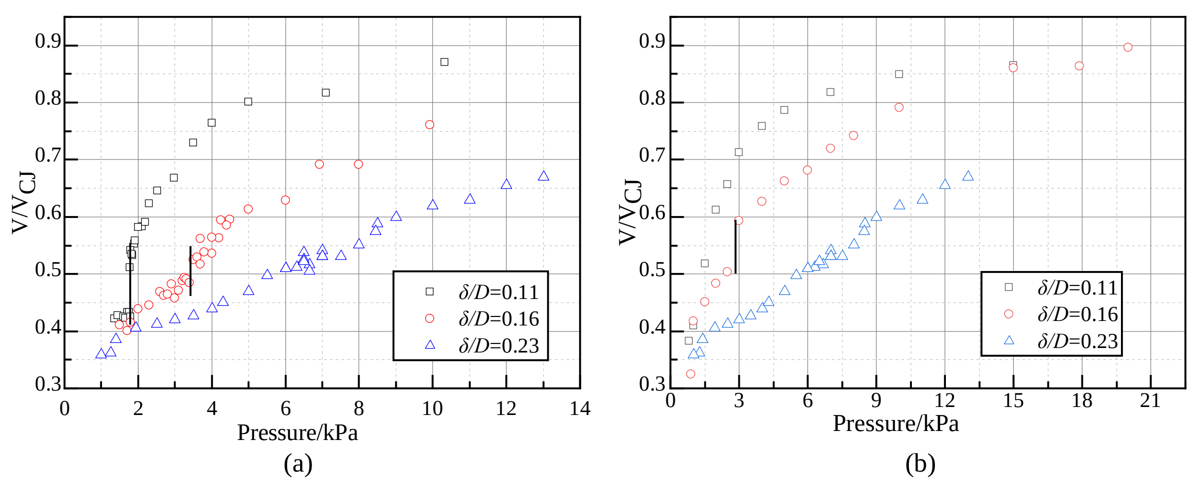


Fig.3 V/V_{CJ} vs. Pressure for C_2H_2+2.5O_2+70%Ar in the 88 mm diameter (a) annularly rough tube (b) circularly rough tube

Figure. 3 shows the velocity of the quasi-detonation or deflagration wave in both the annularly and circularly rough tube. The slope of the detonation trajectory corresponds to the velocity of the detonation. For each case, the slope becomes steady, indicating the wave becomes stable finally. So there is little possibility of a fast-flagration whose velocity is unsteady. For the case with δ/D=0.23 as shown in Fig. 3(a), the detonation velocity far from the limit is about 65% V_{CJ} and continuously decays to about 40% V_{CJ}

towards the detonation limit. For the case with δ/D =0.16, the detonation velocity far from the limit is about 75% V_{CJ} and decreases continuously as the initial pressure decreases. An abrupt drop in velocity is observed at an initial pressure of 3.4 kPa. Below the abrupt drop, the velocity continues to decrease slowly until the failure near 40% V_{CJ}. For the case with δ/D=0.11, the detonation velocity far from the limit is about 85% V_{CJ} and continuously decreases towards the limit. An abrupt drop in velocity is also observed at an initial pressure of 1.8 kPa. The velocity at the limit is about 42% V_{CJ}. In the circularly rough tube as shown in Fig. 3(b), similar phenomena can also be found as compared with that in the annularly rough tube. The velocity, in general, is lower in the annularly rough tube due to the blockage at the core of the tube. For the case with δ/D=0.16 in circularly rough tube, an abrupt drop in velocity is also observed at a lower initial pressure of 2.5 kPa as compared with that in the annularly rough tube (3.4 kPa). However, for the case with largest roughness (δ/D=0.23) and the case with smallest roughness (δ/D=0.11), no observable abrupt velocity drop is found. A possible reason is that, for the case with smallest roughness (δ/D=0.11), the velocity drop is hard to determine as the initial pressure decreases to about 1 kPa; for the case with δ/D=0.23, due to large roughness effect, the velocity is as low as 60% V_{CJ} even at a relatively high initial pressure, which makes it impossible to render a velocity drop occurs. It suggests that the velocity drop which indicates the transition from a quasi-detonation to a high-speed deflagration, must occurs at a certain condition. To examine the transition criterion from a quasi-detonation to a high-speed deflagration, mixtures of C_2H_2+2.5O_2 with different Argon dilution were tested in the annularly rough tube with δ/D=0.11. As shown in Fig.4, abrupt drops in velocity are observed for all the four cases as the wave configuration in the rough tube changing from a quasi-detonation to a high-speed deflagration. The corresponding pressure limit varies with the diversification of Argon dilution. It is obviously that the limit increases with the increase of the Argon dilution.

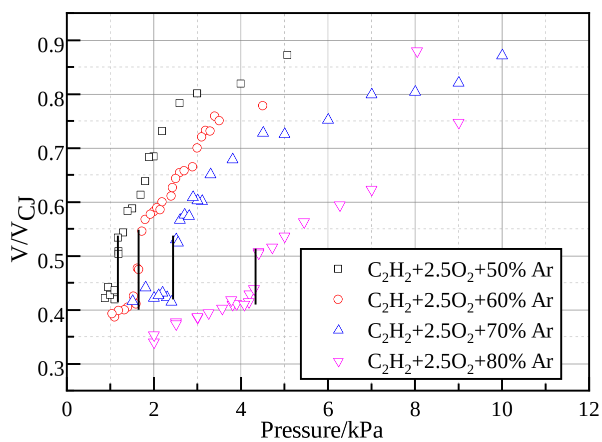
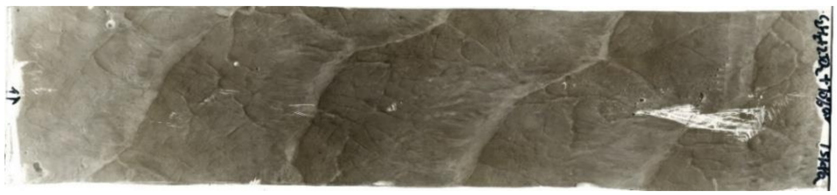


Fig.4 V/V_{CJ} vs. Pressure for C_2H_2+2.5O_2+xAr in the annularly rough tube with δ/D=0.11

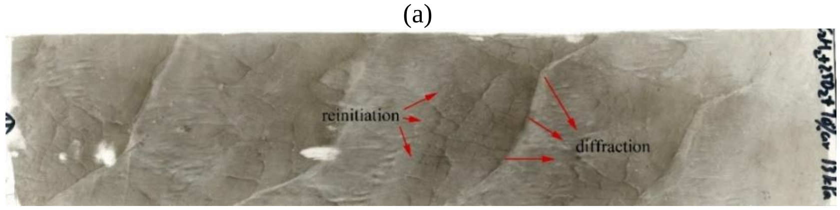
Table 1: Transition limit in circularly rough tube and annularly rough tube

Circularly rough tube				Annularly rough tube			
x	Limit (kPa)	λ (mm)	d/λ	x	Limit (kPa)	λ (mm)	d/λ
40%	1.0	46	1.3				
50%	1.4	43	1.4	50%	1.9	30	1.9
60%	2.2	40	1.5	60%	2.5	30	1.9
70%	2.5	40	1.5	70%	2.8	40	1.5
80%	5.2	45	1.3	80%	6.9	30	1.9

The corresponding limited pressure where the velocity abruptly drops are shown in Table 1. The detonation cell size λ are used to characterize the mixture sensitivity and length scales. Note that the cell sizes used in the present study are obtained from Caltech database [14]. It is found that d/λ≈2 when the velocity drop occurs in annularly rough tube. However, in the circularly rough tube, d/λ≈1.5. A possible reason is that the detonation travels in a two-dimensional case in annularly rough tube, while a three-dimensional case in circularly rough tube.



(a)



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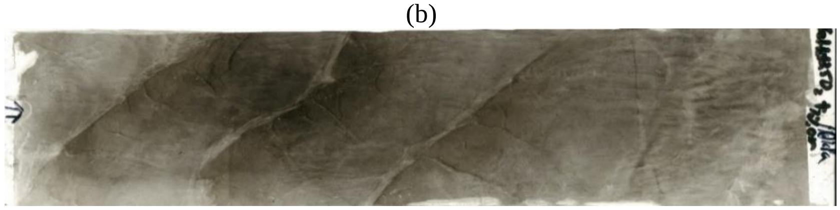
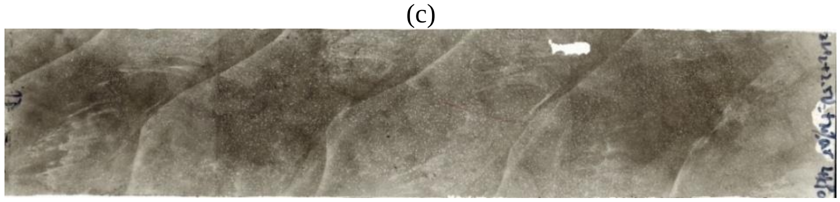
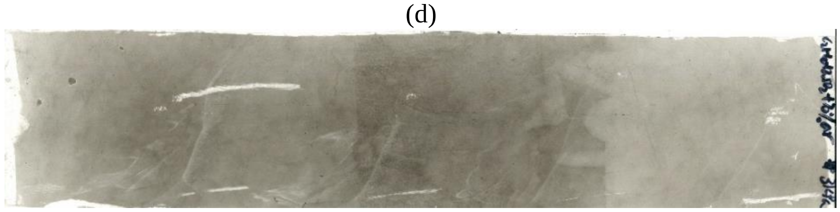


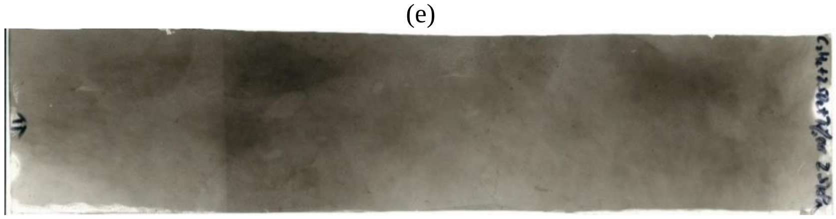
(c)



(d)



(e)



(f)

Fig.5 Smoked foils for C_2H_2+2.5O_2+70%Ar with δ/D=0.16 and initial pressure of (a) 15 kPa, (b) 13kPa, (c) 10 kPa (d) 4 kPa, (e) 3 kPa, (f) 2.5 kPa in annularly rough tube with δ/D=0.11

The detonation velocity does not provide any information on the structure of the detonation front. Thus smoked foils are used to capture the detonation structure as the transition limits are approached. Typical smoked foils for a stoichiometric C_2H_2+2.5O_2+70%Ar mixture in the case with δ/D=0.16 at different initial pressure are shown in Fig.5. The strong roughness in this case can attenuate the detonation by diffraction. However the subsequent reflection downstream on the wall can also reinitiate the detonation front by forming an overdriven detonation (with very fine detonation cells). Note that the detonation travels from left to right. As the initial pressure decreases from 15 kPa to 2.5 kPa, a spinning detonation occurs until approaching the limit where cellular structures disappears. Near the transition limit (2.8 kPa) where velocity abruptly drops, a single-head spin becomes faint indicating the decaying of the detonation and the transition to a high-speed deflagration. The phenomenon that the single-head spin disappears, leaving no trace on smoked foil, demonstrates the transition to a high-speed deflagration as shown in Fig.5(f).

4 Conclusion

On the basis of the present experimental results, it may be concluded that in annularly rough, detonation velocity can vary continuously from close to the theoretical C-J value far from the limit to about 40% V_{CJ} where the detonation fails. The wall roughness promotes the generation of pressure and vorticity fluctuations and hence sustains the quasi-detonation or high speed deflagration. The limit where the velocity abruptly drops indicates the transition from a quasi-detonation to a high-speed deflagration wave. For cases with very large or very small roughness, the abrupt velocity drop cannot be observed instead of a continuous decay in velocity. $d/\lambda \approx 2$ for the case in annularly rough tube, while $d/\lambda \approx 1.5$ for the case in circularly rough tube, which is properly due to the dimension effect. From the observation in smoked foils, as the initial pressure decreases from 15 kPa to 2.5 kPa, a spinning detonation occurs until approaching the limit where cellular structures disappears. Near the transition limit (2.8 kPa) where velocity abruptly drops, a single-head spin becomes faint indicating the decaying of the detonation and the transition to a high-speed deflagration. A self-sustained high-speed deflagration due to the choking effect can also survives in the rough tube.

Acknowledgments

This work was funded by the National Natural Science Foundation of China (No. 11702026), Project of State Key Laboratory of Explosion Science and Technology (QNKT17-02) and Beijing Institute of Technology Research Fund Program for Young Scholars.

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