Propagation Mechanism of Detonations in Rough Walled Tube

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1 Introduction

Considerable attention has been given to flame or high speed deflagration control in orifice plates-filled tubes [1-7]. There have also been numerous studies on the effect of orifice plates on combustion processes such as flame propagation or detonation to deflagration transition (DDT) [7-11]. While these researches do not directly corresponds to the present study where the propagation mechanism of detonations in a 'rough' tube is investigated. The studies of propagation mechanism of detonation in rough tubes with spirals are still lacking. For a Shchelkin spiral, especially with small wire diameter and small pitch, there is an averaged or continuous effect of the spiral by producing 'roughness' on the propagation of the detonation [12]. However, the orifice plates give a 'discrete' effect on wave propagation via disturbance created by the reflection waves. The local phenomena of the interaction between the detonation and the orifice plates or tube wall dominates the propagation, i.e. diffraction through the orifice opening, re-initiation upon reflection of the diffracted wave on the tube wall downstream of the orifice plate, etc., control the propagation phenomena [7]. According to the previous researches, it is found that the deflagration propagation is facilitated in rough walled tubes, while the wall roughness results in a decrease in the detonation velocity. In the present study, velocity measurements and smoke foils were both used in order to provide insight into the detonation propagation. Spirals with three different wire lengths as well as combustible mixtures with various stabilities were used to study the effect of roughness and cellular stabilities on the detonation structures. We also focus on the transition criterion from quasi-detonation to high speed deflagration.

2 Experimental details

The detonation tube used in the present study consists of a 1.6 m long steel driver section with a diameter of 88 mm. Three polycarbonate test tubes of a diameter of 88 mm are attached to the end of the driver tube. The total length of the test section connected by aluminum flanges is 3 m. Detonation is initiated by a high energy spark discharge from a high voltage discharge of a fast inductance capacitor. A short length of Shchelkin spiral was also inserted downstream of the spark plug to promote detonation formation. A driver

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section of 88 mm diameter and 1.6 m long with a much more sensitive mixture was used to facilitate the detonation formation and its initial propagation in the test gas before the boundary effect started to take place. A schematic of the experimental apparatus is shown in Fig. 1. To generate wall roughness, Shchelkin spirals with rectangular cross section of various wire lengths and a pitch of one tube diameter are used. Previous investigations showed that a pitch about one tube diameter is the most effective roughness [10] and also it was found that the phenomenon is not too sensitive to the pitch of the spiral. The diameters of the wire of the spiral used are δ = 10, 14 and 20 mm for the 88 mm tube. The ratio of the wire diameter to the tube diameter δ/D is used to characterize the wall roughness of the Shchelkin spiral, as also shown in Fig. 1.

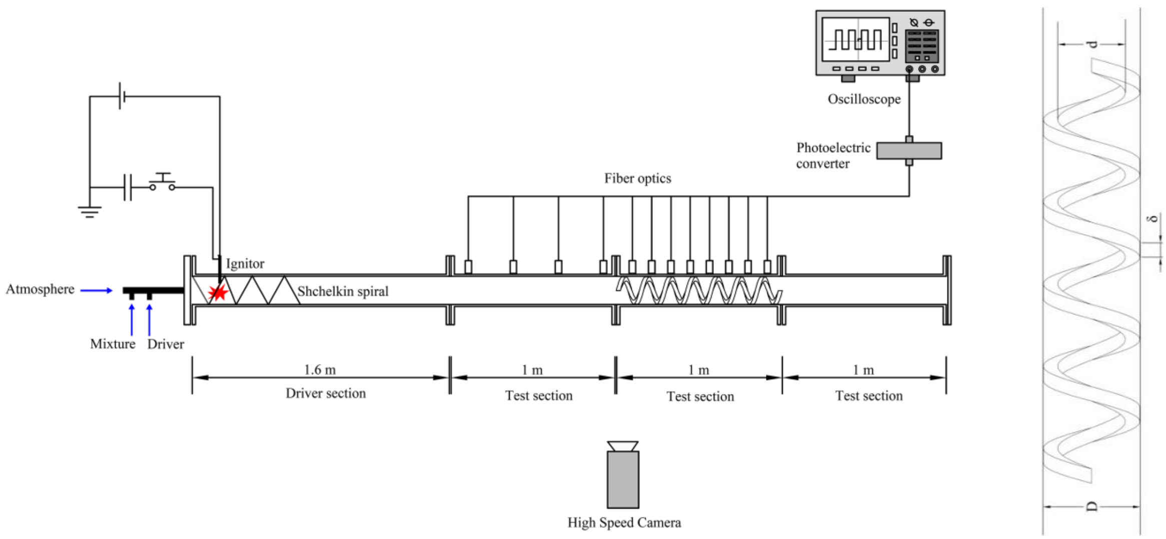
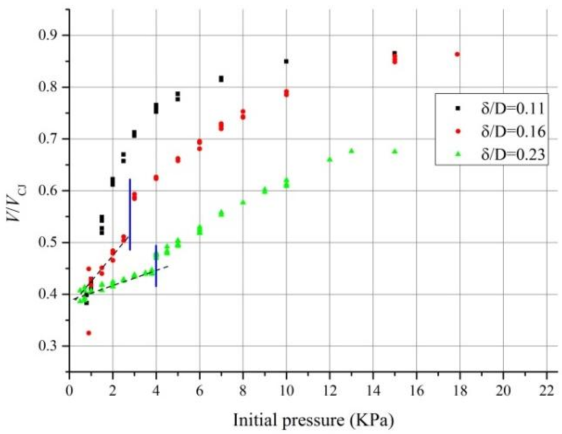


Fig.1 Experimental apparatus and dimensions of the spiral (*D*- tube diameter, *d*- see-through diameter, δ- wire length)

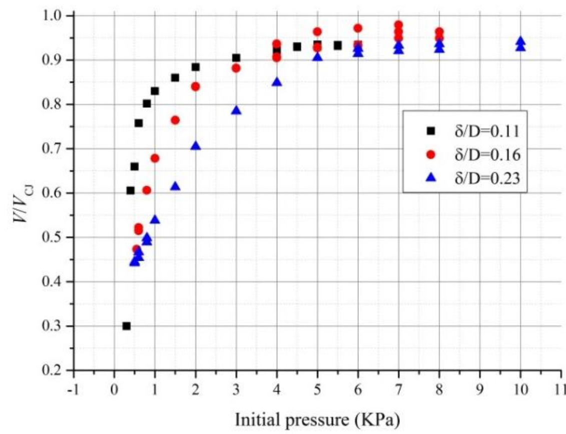
Three combustible mixtures, i.e., C_2H_2+2.5O_2+70%Ar, C_2H_2+2.5O_2, 2H_2+O_2 were used and the choice include those mixtures considered as 'stable' with regular cellular pattern and 'unstable' with highly irregular cell pattern. Fiber optics of 2 mm in diameter connected to a photodiode were spaced periodically along the entire length of the test section. Local detonation velocity was measured from the time-of-arrival of the detonation. A high speed camera was also used to supplement the fiber optic signals when the light from the detonation front becomes weak near the limits. A short length of the smoked foil was inserted near the end of the tube to record the cellular structure of the detonation at the limits. Note that, the foil captures only the detonation core since it is inserted into the inner diameter of the spiral.

3 Results and Discussions

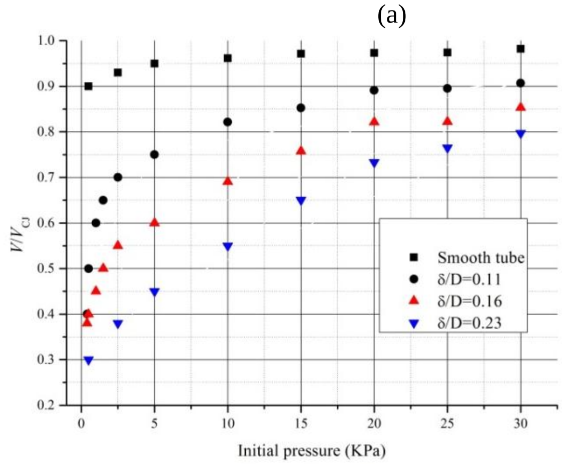
As shown in Fig.2 (a), for δ/D = 0.23, the detonation velocity far from the limit is about 85% V_{CJ} and continuously decays to about 40% V_{CJ} towards the detonation limit. For δ/D = 0.16, the detonation velocity far from the limit is also about 85% V_{CJ} and decreases continuously as the initial pressure is decreased. An abrupt drop in velocity is observed at an initial pressure of 2.8 kPa. After the drop, the velocity continues to decrease slowly. The velocity at the limit is found to be about 40% V_{CJ}. For δ/D = 0.23, the detonation velocity far from the limit is about 68% V_{CJ} and continuously decreases towards the limit. An abrupt drop in velocity is also observed at an initial pressure of 4 kPa. The velocity at the limit is about 38% V_{CJ}. Note that in this case, the detonable mixture of C_2H_2+2.5O_2+70%Ar is a stable case corresponding to regular cellular pattern with relatively large cell size compared to the characteristic length of the rough tube, *D*. Fig.2 (b) shows an unstable case of stoichiometric C_2H_2+2.5O_2 mixture. For the three cases with δ/D = 0.13, 0.16, 0.23, the detonation velocities far from the limit (high initial pressure) are all about 92% V_{CJ} and decreases continuously to about 40% V_{CJ} towards the limit. No abrupt drop is found in this case as shown in the stable case of C_2H_2+2.5O_2+70%Ar. Compared to the C_2H_2+2.5O_2+70%Ar mixture, the stoichiometric C_2H_2+2.5O_2 mixture is more active with high activation energy, more irregular cellular pattern and much smaller cell size. As shown in Fig.2 (c), for a 2H_2+O_2 mixture, the velocity of the detonation gradually decreases as the limit is approached. The velocity in the rough tube at a given pressure is always lower than that of the smooth tube. For a given δ/D, the effect of tube diameter *D* on the velocity is small. For all the three cases, there is a similar velocity behavior regardless of tube diameter *D*. The limit in the rough tube is at a lower pressure and velocity than the limit in the smooth tube. The limiting pressure in rough tubes was determined using velocity measurements. The velocity at the limit was determined to be about 40% V_{CJ}.



(a)



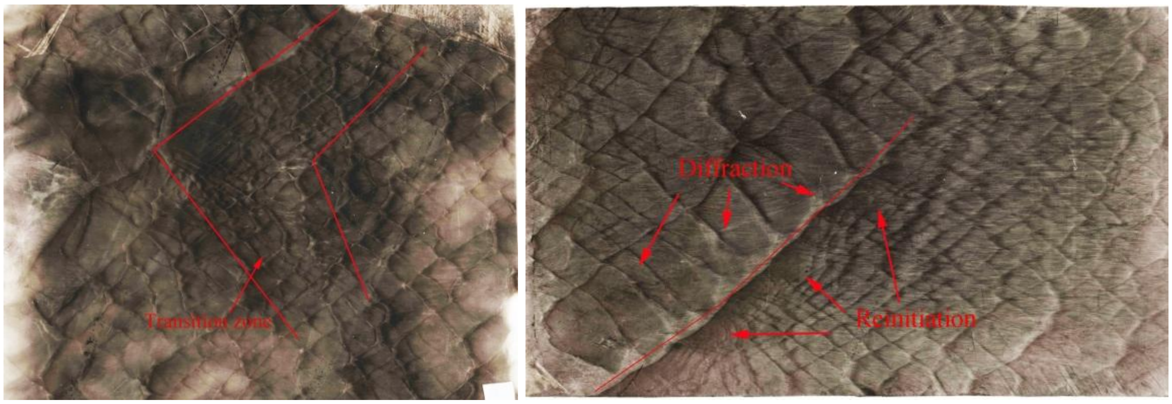
(b)



(c)

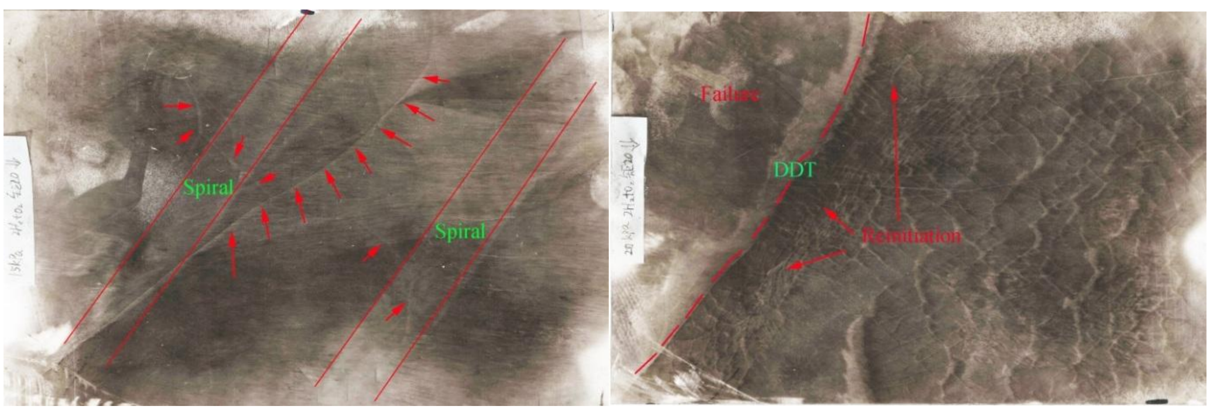
Fig.2 V/V_{CJ} vs. Pressure for (a) C_2H_2+2.5O_2+70%Ar, (b) C_2H_2+2.5O_2, (c) 2H_2+O_2, in an 88 mm diameter tube

The detonation velocity does not provide any information about the structure of the detonation front. Thus smoked foils are used to observe the detonation structure. It is important to note the different means of turbulence production. In smooth tubes, the natural instability of the detonation front produces turbulence. In the rough tubes, the added perturbations at the wall produce turbulence as well which can be considered artificially generated instability. In both cases, the turbulence aids in the propagation of the detonation wave.



(a) (b)

Fig.3 Smoked foils for $2H_2+O_2$ with (a) δ/D = 0.11 and (b) δ/D = 0.16 and initial pressure of 15 kPa

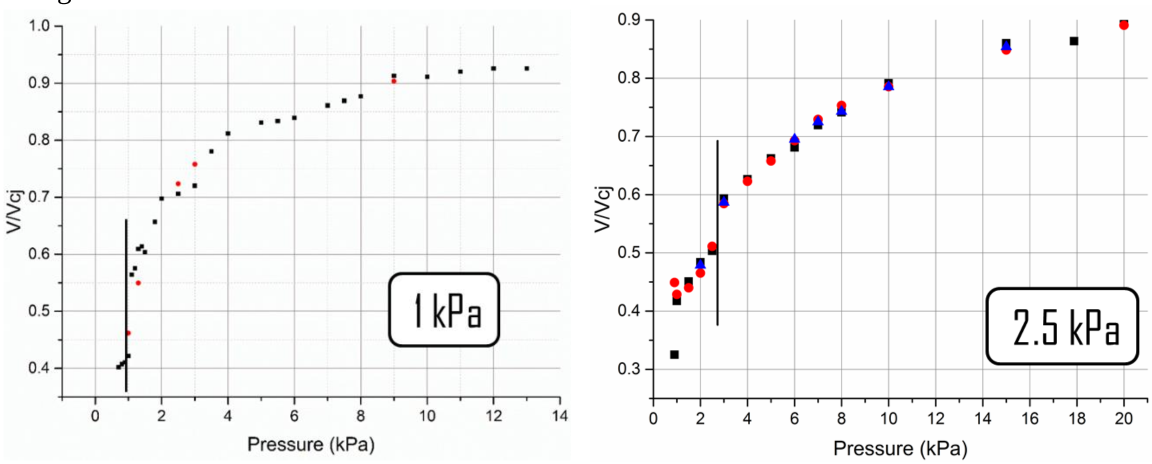


(a) (b)

Fig.4 Smoked foils for $2H_2+O_2$ with δ/D = 0.23 and initial pressures of (a) 15 kPa and (b) 20 kPa

Typical smoked foils for the stoichiometric $2H_2+O_2$ mixture are shown in Fig. 3-4. For δ/D = 0.11 as shown in Fig.3 (a), gradual cell size transition can be found in the vicinity of the spiral. No detonation failure and re initiation are observed in this case. Thus, it suggests that the diffraction due to the spiral wall is not strong enough to attenuate the detonation front. The roughness in this case produces continuous effect on the detonation propagation. For δ/D = 0.16, as shown in Fig.3 (b), detonation failure and re-initiation can be found by comparing the cell sizes near the spiral. 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 small detonation cells). As shown in Fig.4, for the largest roughness, δ/D = 0.23, no intrinsic cellular structures can be observed in the smoke foils except one or two traces on the smoke foil due to the perturbations of reflected waves from the spiral. Thus, it indicates that no detonation exists in the rough tube in this case except a so-called shock-flame complex configuration as suggested by Lee [13]. However, when the initial pressure increases to 20 kPa for the case with δ/D = 0.23, a totally failed zone and a subsequent re-initiation zone with a DDT process is found on the smoke foils as shown in Fig.4 (b). This can be explained that the increased cell member can resist the diffraction effect and the locally failed detonation can recover itself by reflection downstream.

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 an 88 mm diameter tube with δ/D = 0.16. As shown in Fig.5, an abrupt drop in velocity is observed as the wave configuration in the rough tube changing from a quasi-detonation to a high-speed deflagration. It suggests that the transition pressure increases as increasing the Argon dilution, which can also be seen in Table 1. To characterize the mixture sensitivity, the detonation cell size λ can be used. We also found that d/λ=1.3-1.5 when the velocity drop occurs. Note that the cell sizes used in the present study are obtained from Caltech database [14] and [15]. With the same composition and initial pressure, the detonation cell size in a rough tube with momentum loss is usually larger than that obtained in a smooth tube. Thus, d/λ=1 is a more reasonable criterion for the transition. It means at least one detonation cell is need in a rough tube to guarantee the propagation of a quasi-detonation. This criterion found in a rough tube is in accordance with that in a tube with orifices indicating similar mechanism.



(a) C_2H_2+2.5O_2+40%Ar, δ/D = 0.16 (b) C_2H_2+2.5O_2+70%Ar, δ/D = 0.16

Fig.5 V/V_{CJ} vs. Pressure for C_2H_2+2.5O_2 with different Argon dilution in an 88 mm diameter tube

Table 1 Transition pressure and cell size

x	Limit	λ	d/λ
40%	1.0 kPa	46(41) mm	1.3(1.46)
50%	1.4 kPa	43(42) mm	1.4(1.43)
60%	2.2 kPa	40(38) mm	1.5(1.56)
70%	2.5 kPa	40(38) mm	1.5(1.56)
80%	5.2 kPa	45(47) mm	1.33(1.27)

4 Conclusions

Based on the present experimental results, it may be concluded that in rough tubes with spirals, detonation velocity can vary continuously from close to the theoretical Chapman-Jouguet value far from the limits to about 40% V_{CJ} where the detonation fails. This contrasts with the detonations in smooth tubes, where the detonation velocity seldom decreases to less than 80% V_{CJ} at the limits. It suggests that wall roughness tends to facilitate the self-sustained propagation of detonation waves. We also found that an abrupt drop in velocity exists when decreasing the initial pressure for mixtures with high argon dilution, indicating a transition from a quasi-detonation to a high speed deflagration. Further study shows the transition criterion from a quasi-detonation to a fast deflagration in a rough walled tube, i.e., d/λ=1.

Acknowledgment

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