# Detonation Propagation in Rough Tube

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## 1 Introduction

Wall roughness is found to have a large influence on the propagation of detonation waves. Velocity in rough tube can vary between 90% of theoretical Chapman–Jouguet velocity to as low as 40% $V_{CJ}$. The mechanisms of propagation of detonation in rough tubes are very complex and generally credited to the generation of pressure waves and turbulence by the rough wall in the reaction zone. Turbulence has a negative effect on the propagation by increasing losses, but it also has a positive effect in promoting mixing which facilitates ignition and increasing the reaction rates. The negative effect is indicated by the increase in velocity deficit[1] whereas the positive effects lead to the extension of the detonation limit[2].

The majority of the previous studies in rough tubes are based on the use of repeated orifice plates in the tube[3-5]. The dimensions of the orifice of the obstacles and spacings are of the order of the tube diameter itself. Thus the phenomenon is more of the diffraction of the detonation by the orifice plates and reignition by shock reflections. Studies that can be considered as rough walls are the original work by Laffitte [6] who placed sand grains on the tube wall, and the use of wire spiral by Shchelkin[7], Guenoche[8], and Brochet[9]. Recent studies using wired springs were also made by Starr[2], Monette[1] and Zhang[10]. However their studies were limited to a narrow range of conditions, i.e. spring parameters, different explosive mixtuers, and initial pressure range.

The present study extend the previous works of Starr[2] and Monette[1]. In addition to velocity measurements, smoked foils were also used to observe the effect of roughness on the detonation structure.

## 2 Experimental Details

Experiments were performed in a transparent detonation tube, shown in Fig.1. The tube consists of a driver section followed by a smooth section prior to the rough section. The driver section is 60mm in diameter and 1.1m in length, and a Shchelkin spiral is inserted to facilitate the DDT process. The diameter of smooth and rough section is 49.4mm and the length is 1.4m and 1.9m respectively. A high energy spark is used to ignite the mixture in the driver section. Ionization probes were installed evenly along the smooth and rough section to obtain the time of arrival data for velocity measurement. Smoke foils are also used to register the cellular structure of the gaseous detonation wave.

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Both stable ($C_2H_2$+2.5$O_2$+70%Ar) and unstable ($C_2H_2$+5$N_2O$) mixtures are used in our study. A readily detonable mixture ($C_2H_2$+$O_2$) is used as the driver gas in the driver section. The rough section is formed by inserting different wire springs into the tube. The wall roughness is characterized by the ratio of wire diameter to tube diameter σ=δ/D, and the pitch to tube diameter ratio φ=λ/D.

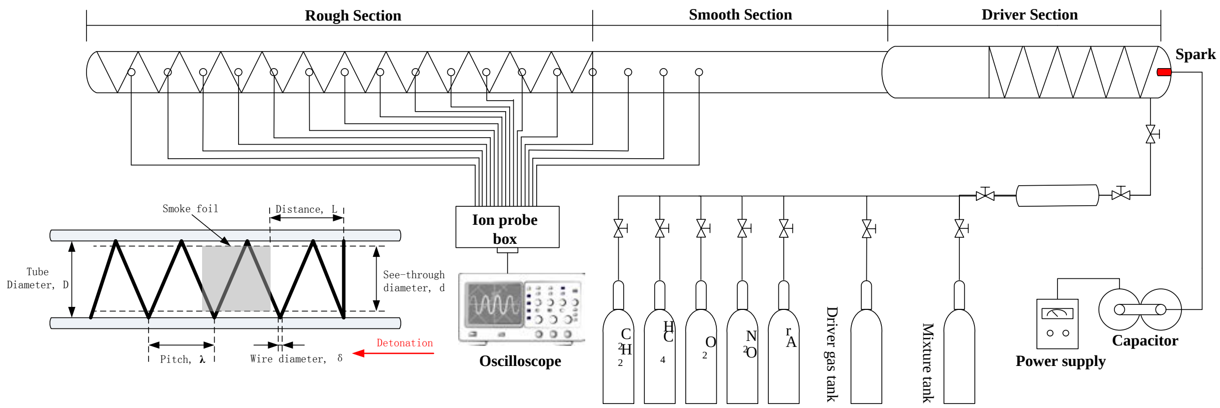


Fig1. Experiment Setup and Sketch of the Shchelkin Spiral and Smoked Foil in The Test Section

## 3 Results and discussion

The variations of the detonation velocity with distance are obtained for different roughness parameters at different initial pressures. Typical results of the detonation velocity for $C_2H_2$+2.5$O_2$+70%Ar for the roughness parameters σ=0.06 and φ=0.48 are presented in Figs 2-5. Similar results are observed for other value of tube roughness. The velocity is divided by the theoretical CJ velocity to make it dimensionless. Experiments at the same condition are repeated for least two or three times to ensure reproducibility.

Fig.2 shows the plot of detonation velocities versus distance at an initial pressures of 6kPa. Prior to entering the rough section of the tube, the detonation velocity is found to be typically about 92% of the CJ velocity. Upon entering the rough section, the velocity drops abruptly to about 75% of the CJ velocity within a short distance of travel of about one tube diameter. The detonation then propagates thereafter in the rough section at a relatively constant velocity.

The velocity at lower initial pressure of 3kPa and 2.5 kPa are shown in Fig.3 and Fig.4 respectively. In the smooth section, the typical velocity is about 88% of the CJ velocity, however upon entering the rough section, both the velocity deficit and the fluctuation of the local detonation velocity increase. For initial pressure of about 3kPa (Fig.3), the detonation velocity in the rough section is found to decay continuously without achieving a steady value for the 1.5 m length of travel of the tube. It may be possible that the detonation will eventually decay to a lower velocity corresponding to a high speed turbulent deflagration for longer distances of travel. The detonation is also found to be highly unstable and the local detonation velocity has very large fluctuations.

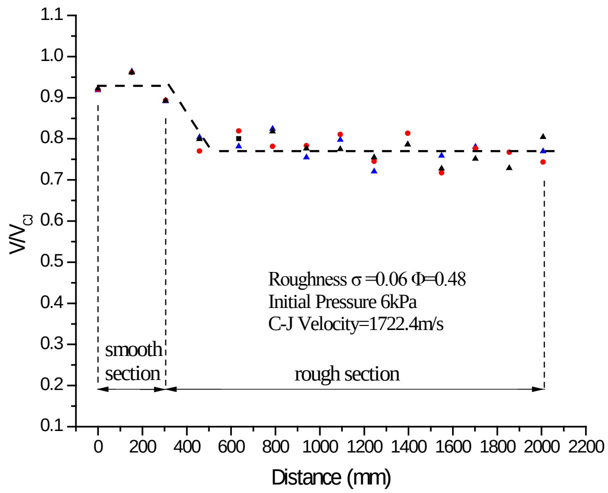


Fig.2 Local velocity plots at 6 kPa

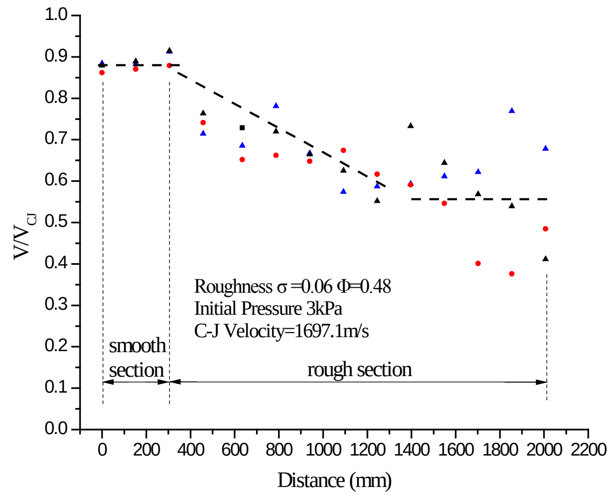


Fig.3 Local velocity plots at 3 kPa

For still lower initial pressure of 2.5kPa and below, the velocity decays to a steady value of about $0.4V_{CJ}$ after propagating for about 25 tube diameters in rough section. At even lower initial pressure of 1.5 kPa (Fig.5), the detonation is found to decay to the steady value of about 40% of the CJ value more rapidly. This result seems to suggest that at very low initial pressures, the detonation propagates in a different regime with a velocity of about $0.4V_{CJ}$. The wave may be a high speed turbulent deflagration where the tube roughness creates sufficient turbulence to maintain the high speed propagation of the combustion wave. However the propagation mechanism differs from that of a detonation wave. Smoked foils can confirm if the wave has a cellular structure.

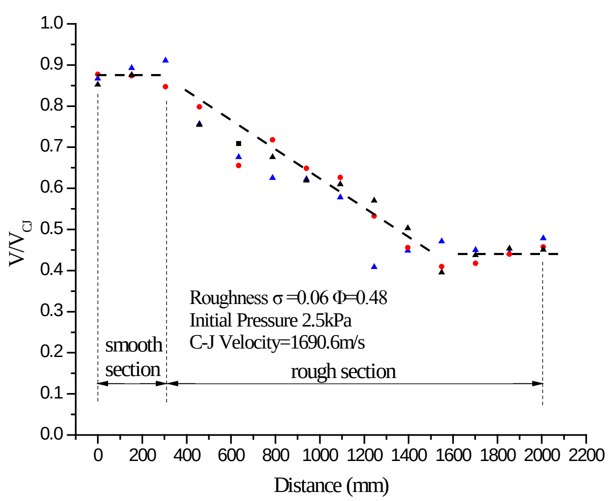


Fig.4 Local velocity plots at 2.5 kPa

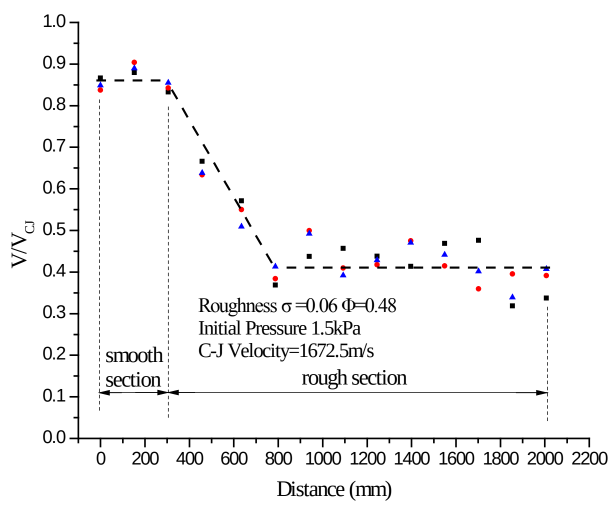


Fig.5 Local velocity plots at 1.5 kPa

For a given mixture and wall roughness, it appears that there is a change in the combustion wave propagation mechanism at some critical initial pressures. For the case mentioned above ($C_2H_2$+2.5$O_2$+70%Ar, σ=0.06 and φ=0.48), the critical pressure is around 3kPa. When the initial pressure is higher than 3kPa, the detonation decays to a steady velocity and maintains at this value for the entire rough section. When the initial pressure is around 3kPa, the detonation keeps decaying in the rough section and the detonation becomes highly unstable. When the initial pressure is lower than or equal to about 2.5kPa, the detonation velocity decays to a steady velocity of about 40% CJ velocity in the rough section. When initial pressure is even lower than 1.5kPa, no self-sustained combustion waves are observed. It may be concluded that in a rough tube, the velocity deficit increases with decreasing initial pressures until a critical pressure where the detonation fails and decays to a high speed deflagration of about 40% $V_{CJ}$. The decay is more rapid with decreasing pressure until the limit when no self-sustained combustion wave is observed in the rough section.

To obtain a better understanding of the mechanism of propagation of the detonation in a rough walled tube, smoke foils are inserted into the rough walled tube at different position to register the cellular structure of the detonation. Short strips of smoked foil are inserted in the rough section and these short strips are found not to influence significantly the wave structure. Fig.6 shows typical smoke foils for the detonation conducted in the mixture of $C_2H_2$+2.5$O_2$+70%Ar at an initial pressure of 6kPa at different positions along the rough walled tube. Prior entering the rough section, regular multi-headed cellular structure can be observed in the smooth section and the cell width is about 19.4mm. In the rough section, the detonation cell size becomes progressing larger as it propagates along the tube. The initial multi-headed structure progressively decay to single-headed spin detonation and remains at this structure to the end of the tube.

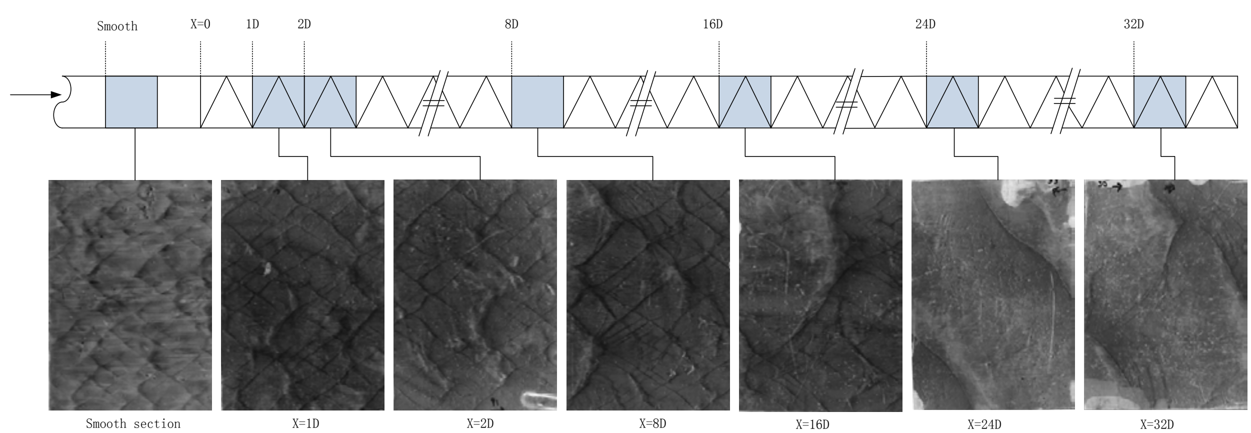


Fig.6 Smoked foil for initial pressure of 6kPa

Fig.7 shows the smoke foils of the detonation conducted at an initial pressure of 2kPa. Double-headed structure with the cell width(~140mm) of the order the tube diameter can be observed in the smooth section. Once the detonation transmits into the rough section, the cell size increases and the structure transforms rapidly to single-head spin wave structure after propagating a distance of only one tube diameter. The single-head structure remains for a short distance of about 3-4 tube diameter, then the cellular structure disappears gradually and no cellular structure is registered on the smoke foils after propagating for a further 8 tube diameters long. The failure of detonation is due to the tube diameter being barely large enough to support a detonation. These smoke foils without cell structure verifies that the combustion wave became a high speed turbulent deflagration in a given rough-walled tube when the pressure is very low.

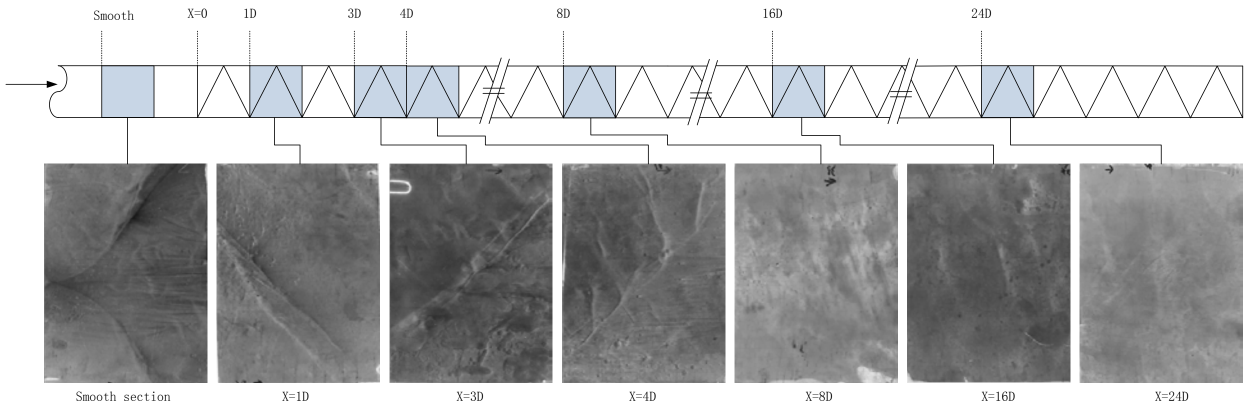


Fig.7 Smoked Foil for spring #3 in low pressure range (2kPa)

It may be concluded that wall roughness tends to interfere with the intrinsic cellular instability of the detonation and turn the initial high mode to a lower mode instability. This observation is compatible to the streak schlieren observation of Brochet[11]. It may also be concluded that in the low velocity regime of $V \approx 0.4V_{CJ}$, cellular structure is absent indicating the combustion wave propagates in a different regime, i.e. as a high speed deflagration.

The variation of average detonation velocity with initial pressure for $C_2H_2$+2.5$O_2$+70%Ar is shown in Fig.8. It can be seen clearly that for a given wall roughness, the velocity deficit increases with the lower initial pressure until the critical value. Then the velocity takes an abrupt jump to a low value of about 40% CJ velocity. For roughness with the larger wire diameter, the velocity decays more rapidly and the critical pressure is higher. When initial pressure is lower than the critical value, the velocity decreases slowly around $0.4V_{CJ}$ with the decreasing pressure until 1.5kPa below which no more combustion waves were observed.

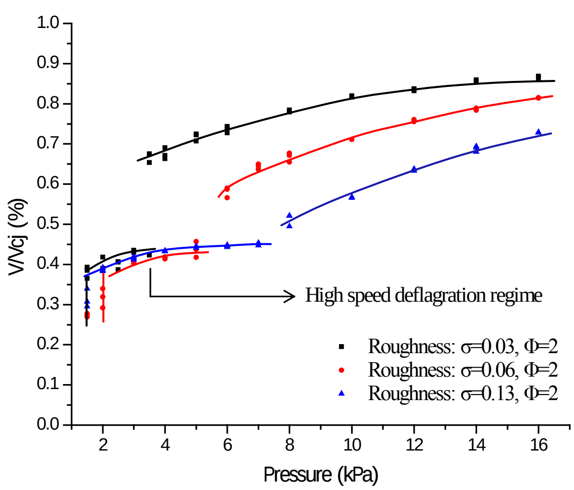


Fig.8 Velocity versus initial pressure for different wall roughness

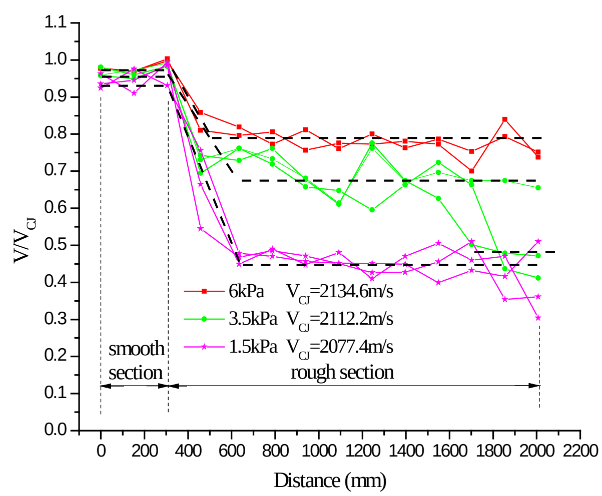


Fig.9 Velocity plots for $C_2H_2$+5$N_2O$ (σ=0.06, φ=0.13)

Experiments were also conducted for unstable mixture of $C_2H_2$+5$N_2O$. Fig.9 shows the variation of detonation velocity with distance for $C_2H_2$+5$N_2O$ with the roughness parameters σ=0.06 and φ=0.13.

There are also three different regimes observed at different initial pressures. At high pressure of 6kPa (higher than the critical value), the detonation velocity sustains at a value of about 80% CJ velocity as the detonation enters the rough section. For lower initial pressure at 3.5kPa (around the critical value), the detonation is highly unstable and the velocity decays continually in the rough section with large fluctuation. For even lower pressure (lower than critical value), the velocity decays rapidly to about $0.45V_{CJ}$ once it transmits into the rough section. These similar velocity tendency indicates that the combustion wave becomes high speed deflagration in rough-walled tube at low pressure for both stable and unstable mixtures. For high speed deflagration, there is an absence of cellular structure.

## 4 Conclusions

The present study of detonation propagation in rough tubes has a large velocity deficit at some critical pressures, there is an abrupt jump to a different propagation regime of high speed deflagration of about $0.4V_{CJ}$. Smoked foil records indicate tube roughness has a destructive interference with the cellular structure reducing a multi headed wave to a single headed spin wave. In the high speed deflagration regime, cell structure is absent indicating a different mechanism of propagation.

## Acknowledgement:

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