# Detonation limits in rough walled tubes

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**ABSTRACT**

The present thesis reports the results of an experimental study of detonation limits in rough tubes. Detonation velocity is measured by photodiodes and ionization probes spaced at 10 cm intervals along the length of the tube. Short lengths of smoked foils inserted into the core of the rough tube is used to register the structure of the detonation wave. The results indicate that in rough tubes, the detonation velocity is generally much lower than the corresponding values for smooth tubes. The velocity decreases slowly at first and then more rapidly as the limit is approached. The velocity variation is generally continuous and at the limits, the failure velocity is of the order of about 0.4 $V_{CJ}$ for all cases. The detonation limits in rough tubes are found to be wider than for a smooth tube. This indicates that the turbulence generated by the wall roughness facilitates the propagation of the detonation and extends the limits. Smoked foil records show that in the core of the rough tube the detonation front has a cellular structure corresponding to the usual cellular structure due to instability of the detonation. Thus the intrinsic unstable cellular structure is quite robust and retains its global characteristics in spite of the large perturbations generated by the rough wall. The detonation in the core of the rough tube goes from multi-headed to single headed as the limit is approached. Past the single headed spin, the low velocity detonation has no cellular structure but consists of interacting weak transverse waves from the rough wall.

## ABRÉGÉ

La présente thèse expose les résultats d'une étude expérimentale des limites de détonation dans des tubes rugueux. La célérité de détonation est mesurée par des photodiodes et des sondes d'ionisation espacées à des intervalles de 10 cm le long du tube. De courts segments de feuilles de suie insérés dans le noyau du tube rugueux sont utilisés pour visualiser la structure de l'onde de détonation. Les résultats indiquent que dans des tubes rugueux, la célérité de détonation est généralement beaucoup moins élevée que les célérités correspondantes pour tubes lisses. La célérité diminue lentement au début, puis plus rapidement alors que la limite est approchée. La variation de célérité est généralement continue et à la limite la célérité est de l'ordre d'environ 0,4 $D_{CJ}$ (la célérité de détonation CJ) dans tous les cas. Les limites de détonations dans des tubes rugueux se sont révélées être plus étendues que pour un tube lisse. Ceci indique que la turbulence générée par la rugosité de la paroi facilite la propagation de la détonation et repousse ses limites. Les feuilles de suie montrent que, dans le noyau du tube rugueux, le front de détonation a une structure cellulaire correspondant à la structure caractéristique de l'instabilité de la détonation. Ainsi, la structure cellulaire instable et intrinsèque étant très robuste, elle conserve ses caractéristiques globales en dépit des grandes perturbations générées par la paroi rugueuse. La détonation dans le noyau du tube rugueux passe d'une structure multidimensionnelle au régime hélicoïdal alors que la limite est approchée. Passé le régime de rotation hélicoïdale, la détonation à basse vitesse de propagation n'a pas de structure cellulaire, mais se compose d'interactions de faibles ondes transversales générées par la paroi rugueuse.

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# CHAPTER 1
# Introduction

## 1.1 General Overview

The present thesis investigates the detonation limits in rough walled tubes. The initial pressure of the detonation is lowered until it no longer propagates. It is now considered failed, and the propagation limit has been found. It is of interest to compare such limits with the limits found in smooth tubes.

There has been no previous work on the detonation limits in rough walled tubes. However, there have been studies which observed the detonation propagation and structure in rough walled tubes. [1–5]

There have also been numerous studies on the effect of obstacles on combustion processes such as flame propagation or detonation to deflagration transition (DDT). [6–9] While these do explore the propagation regimes of such phenomena using orifice plates, they do not directly relate to the present study where the limits of a self-propagating detonation in a “rough” tube are investigated. It should also be noted that repeated orifice plates used as obstacles in the previous studies differ from the Shchelkin spiral used as roughness in the present study, especially if the wire diameter is not large. In the orifice plates, the local phenomena of the interaction between the detonation and the orifice plates dominates the propagation, i.e. diffraction through the orifice opening, reinitiation upon reflection of the diffracted wave on the tube wall downstream of the orifice plate, etc., control the propagation phenomena. In the Shchelkin spiral, especially with small wire diameter and small pitch used in this study, there is an averaged effect of the spiral producing “roughness” on the propagation of the detonation.

The addition of roughness to the wall is a boundary condition problem where the detonation front is being constantly perturbed, thus generating turbulence. For high speed compressible supersonic flow, turbulence consists of strong transverse pressure waves as well as velocity fluctuations. Dupré [10] showed that when the transverse waves associated with cellular instability of the detonation front are attenuated in a porous walled tube, the detonation fails. Thus the transverse pressure waves are essential for detonation propagation. The addition of transverse waves will lead to changes in the detonation limit when compared to that of a smooth tube. In smooth tubes, the detonation velocity seldom drops below 80% of the Chapman-Jouguet velocity ($V_{CJ}$) when failure occurs. In rough walled tubes, a detonation velocity as low as 50% $V_{CJ}$ has been observed within the limits. This low velocity cannot be observed in a smooth tube since the detonation will have failed. However in the rough tube, it is still a self-sustained propagating detonation wave.

### 1.2 Literature Review

The early studies which implemented additional roughness in tubes were interested in its effects on the detonation to deflagration (DDT) phenomenon and flame propagation. Lafitte (1923) [11] used a strip of coarse sand on the inside tube wall and observed shorter distances for the transition from deflagration to detonation when compared to that of a smooth wall. Chapman and Wheeler (1926) [12] placed obstacles in a tube and were able to obtain flame speeds in the order of a few hundred of meters per second. For a methane - air mixture, a mixture generally considered insensitive, this is quite a high speed. Shchelkin (1940) [13] increased the wall roughness of the tube by placing a spiral coiled wire inside. Transition distances were demonstrated to be two orders of magnitude less than in a smooth tube. Detonation wave speeds as low as 50% $V_{CJ}$ were observed.

Later on, the effect of roughness on the propagation and structure of detonations were studied.

Guénoche (1949) [1] performed experiments measuring detonation velocity in different tube diameters ($D$) using a spiral coiled wire inside the tube. The wire diameter ($\delta$) and the pitch of the spiral was varied. It was observed that the velocity decreases with increasing $\delta/D$. Detonation velocities as low at 40% $V_{CJ}$ were measured. It was suggested that the velocity is linked to the wave stability.

Manson et al. (1963) [2] and Brochet (1966) [3] utilized streak Schlieren photography to study detonations in rough tubes using a spiral. Similar experiments were conducted in smooth tubes for comparison. The nitrogen dilution of the propane mixture was varied to obtain different degrees of readily detonable mixtures (low dilution) to limiting mixtures (high dilution). For the range of studied dilutions in the rough tube, horizontal streaks near the detonation front appeared in all photographs whose frequency corresponded to the pitch of the spiral. For a so-called "stable" detonation, or readily detonable, the roughness produced a velocity deficit of up to 10%. Striae associated with single-head spin were observed for a more "stable" detonation in the rough tube, whereas they only appeared for a more "unstable" detonation (higher dilution) in the smooth tube. For the limiting mixtures, the shock front and combustion wave were completely dissociated yet remained coupled. They continued to propagate at the same speed while separated by a distance. This distance increased with increasing dilution, thus for more limiting mixtures the shock front and the combustion wave were further apart. It was suggested that the spiral decelerates the velocity of the shock wave, while accelerating the velocity of the combustion wave, thus allowing them to propagate at a constant velocity together. A velocity deficit of 40-50% was observed. This is similar to the dissociation that occurs in smooth tubes where the shock front and combustion wave would separate but would propagate at different speeds, thus failure occurs. In agreement with Guénoche, it was found that the velocity deficit is connected to the stability of the detonation wave.

Teodorczyk et al. (1988, 1991) [4,5] studied the propagation of quasi-detonations in rough tubes using high speed Schlieren photography. The velocity of the quasi-detonations varied from 50% $V_{CJ}$ to $V_{CJ}$ depending on the mixture parameters. The propagation mechanism of such detonations was found to be the continuous re-initiation and attenuation by diffraction around the obstacles. The re-initiation, controlled by the obstacles, can be caused by shock reflections (transition from a regular to a Mach reflection) at the walls which engulf the failed detonation front. It may also occur through strong transverse shock interactions. This is similar to the ignition mechanism in normal cellular detonations. When the shock reflections were damped out using fine wire screens, the transition to the quasi-detonation wave was delayed; thus demonstrating the importance of shock reflections to the re-initiation of the detonation.

## 1.3 Current Study

Indeed it is found that detonation propagation is facilitated in rough walled tubes although wall roughness results in a decrease in the detonation velocity. Hence if turbulence generated artificially in rough walled tubes can facilitate detonation propagation, then it is reasonable to assume that the detonation limits should also be wider in rough walled tubes. The influence of wall roughness on detonation limits has not been investigated to date. It is of interest to determine if turbulence can extend the detonation limits. The current study concentrates on determining the detonation limiting pressure and velocity as well as its corresponding detonation structure in rough tubes.

# CHAPTER 2
# Experimental Details

## 2.1 Experimental Set-up

A schematic of the experimental set-up is shown in Fig. 2–1. A 1 m long steel driver section of 60 mm diameter is used for initiating the detonation in the experiment. A small volume of more sensitive mixture ($C_2H_2$ + $O_2$) is used to ensure a detonation is formed in the test section. Detonation tubes of diameters $D$ = 12.7 mm and $D$ = 50.8 mm were used in the present study. The test section is 1.5 m long and the obstacle (rough) section is 1 m. An initial 0.5 m length of a smooth section to is used provide a reference detonation velocity prior to its entry into the rough section. It was found that the detonation adjusts rapidly (within a couple of tube diameters in general) upon entering the rough section. Thus there is no need to use a long rough section for the experiments.

It should be noted that the smooth limits in the given tubes have been determined by Gao et al. [14]. Once the initial pressure in the experiment is decreased past the limiting pressure found by Gao, the detonation is now considered failed. Therefore, the smooth section is rendered useless since the detonation can no longer propagate. When this occurs it is necessary to extend the rough section all the way to the driver.

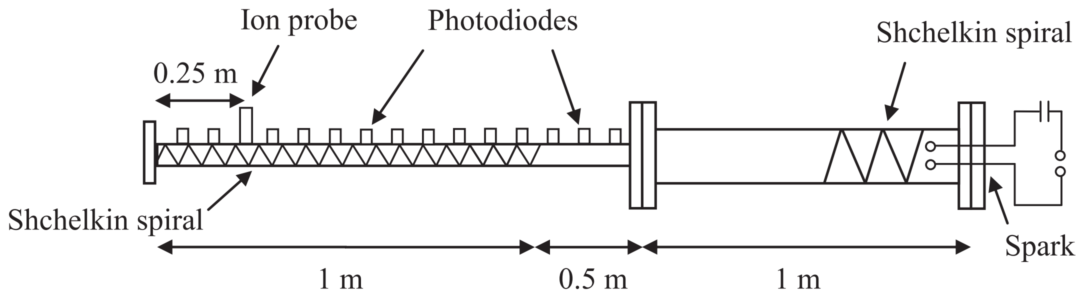


Figure 2–1: Schematic of Experimental Set-Up

To generate wall roughness, a Shchelkin spiral of various wire diameter and a pitch of one tube diameter was used. Previous investigations indicated that a pitch about one tube diameter is the most effective roughness [6] 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 were $\delta$ = 1.6 and 3.2 mm for the 12.7 mm tube and for the larger tube of 50.8 mm, the wire diameters used were $\delta$ = 6.4 and 9.5 mm. The ratio of the wire diameter to the tube diameter $\delta/D$ is used to characterize the wall roughness of the Shchelkin spiral. The spiral characteristics are shown in Fig. 2–2.

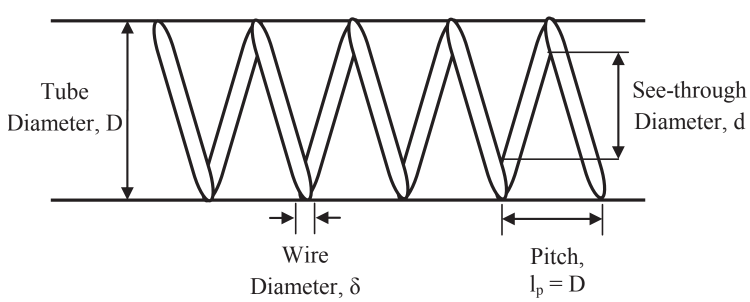


Figure 2–2: Wall Roughness

Pre-mixed mixtures of $C_2H_2$ + $2.5O_2$ + 70% Ar and $CH_4$ + $2O_2$ were used. The former mixture represented a so called "stable" mixture with detonations having a regular cellular pattern whereas the methane mixture represents an "unstable" mixture with irregular cell pattern. Equimolar $C_2H_2$ + $O_2$ (a readily detonable mixture) is injected into the driver section to promote the initiation of a detonation in the less sensitive test mixture. The mixtures are prepared via the partial pressure method and left to settle for 16 hours to allow for proper mixing. The mixture in the driver section is detonated by a high energy spark from the high voltage discharge of a low inductance capacitor (15 kV and 0.2 $\mu$F).

### 2.2 Diagnostics

Velocity measurement was effected by regularly spaced fiber optics (10 cm apart) along the length of the test section. The optic fibers were more closely spaced near the beginning of the coil as to capture the adjustment of the detonation when entering the rough section. An ionization probe was also used to supplement the fiber optic signals when the light from the detonation front becomes weak near the limits.

Smoked foils were employed to record the cellular structure of the detonation at the limits. A short length of the smoked foil is inserted near the end of the tube. The foil captures only the detonation core since it is inserted into the inner diameter of the spiral. Although the smoked foil shields the detonation from the roughness at the wall, it is found that the detonation structure is retrained for some distance of travel after entering the smoked foil section. Thus the foil can register the detonation structure in the rough tube.

# CHAPTER 3
# Results and Discussion

In the present study of detonation limits in rough tubes, the primary diagnostic is velocity measurement. This is effected through the use of photodiodes and ion probes. Photodiodes record the time of arrival of the detonation wave along the tube which allows for a detonation trajectory to be determined. The slope of the detonation trajectory corresponds to the velocity of the detonation. At lower pressures when the luminosity of the detonation wave has decreased, the ion probe supplements the photodiodes. The photodiode signals become erratic and not all of them are triggered. The ion probes can generally give a signal even when the photodiodes do not register a signal. Combining with photodiode signals, it is possible then to determine if a steady detonation wave is obtained. The detonation limit in rough tubes is defined when no steady wave is observed. The limit is arrived at by decreasing the initial pressure of the detonation.

For a given mixture, tube diameter $D$, and wire diameter $\delta$, the limit is approached by lowering the initial pressure. At an initial pressure far from the limit, the velocity deficit is generally small, but the deficit increases as the limit is approached. The steady detonation in the initial smooth section serves as a reference. In general, it is found that the detonation adjust to the wall roughness rapidly upon entering the rough section.

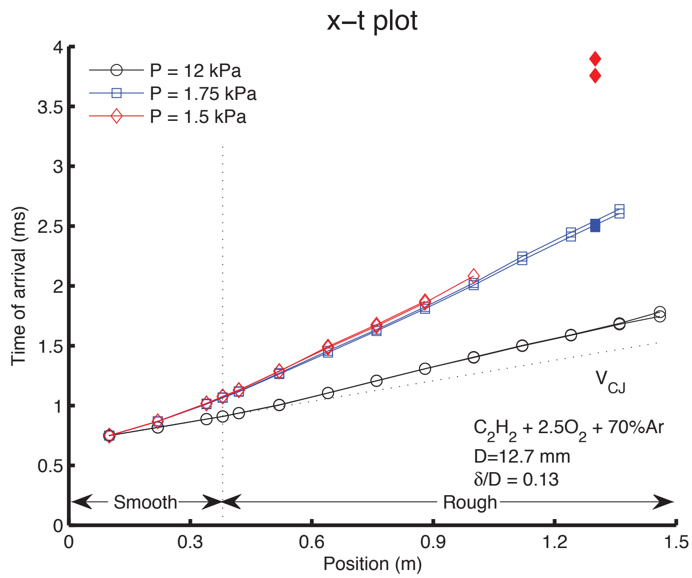


Figure 3–1: Detonation trajectories for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 12.7 mm diameter tube with $\delta/D = 0.13$ with varying pressures showing the progression towards the limit

Fig. 3–1 illustrates typical detonation trajectories for $C_2H_2$ + $2.5O_2$ + 70% Ar in a 12.7 mm diameter tube with $\delta/D$ = 0.13. The open symbols represent the photodiode signals and the colored symbols represent the ion probe signal. It is found that one ion probe signal suffices to indicate if a combustion wave has propagated to the end of the test section. For initial pressures far from the limiting value (12 kPa), the detonation trajectory in the initial smooth section of the tube is straight with a slope corresponding closely to the CJ velocity. Note all CJ calculations are computed using the NASA CEA program [15]. When the detonation enters the rough section, it adjusts rapidly within a few tube diameters and the slope of the trajectory changes to indicate a lower detonation velocity. It is found that the detonation propagates at a constant velocity in the rough section when the condition is within the limits. As the initial pressure is decreased towards the limit, the trajectory in the rough section still continues to be a straight line indicating a steady detonation velocity. Since the detonation limit in a smooth tube occurs before the limits in a rough tube, we have to eliminate the initial smooth section when the condition is past the smooth tube limits. Beyond the limit (at 1.5 kPa), we note from the long time delay registered by the ion probe at the end of the test section that the detonation wave failed and a deflagration with a much reduced velocity is obtained.

From the detonation trajectory, the detonation velocity can be determined. A local velocity can be obtained from adjacent photodiode signals. Previous studies [14, 16] in smooth tubes have reported the presence of "stuttering" or galloping detonations near the limits. In the rough tube, no such longitudinal fluctuations are observed.

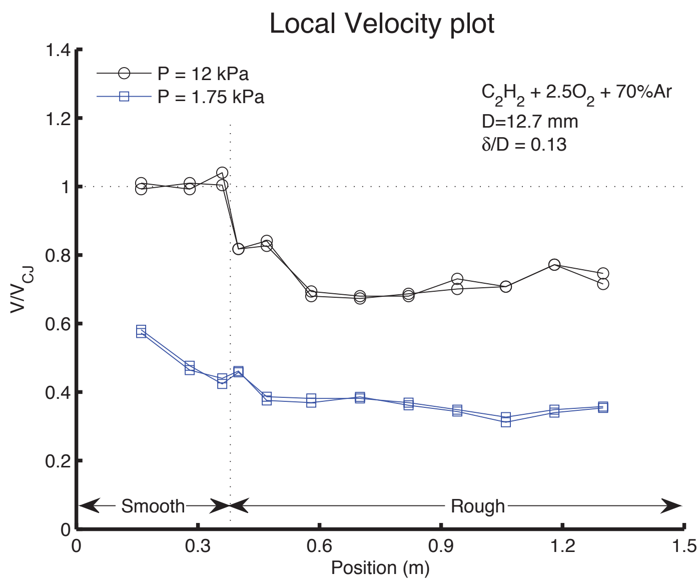


Figure 3–2: Local velocities for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 12.7 mm tube with $\delta/D$ = 0.13 with varying pressures showing the progression towards the limit

Fig. 3–2 illustrates the local velocities for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 12.7 mm tube with $\delta/D$ = 0.13. For initial pressures far from the limits (12 kPa), the detonation velocity in the smooth section of the tube corresponds closely to the CJ velocity of the mixture. When the detonation enters the rough section, it adjusts rapidly within a few tube diameters of propagation to a lower detonation velocity. As the initial pressure is decreased further towards the limit, the velocity decreases also. It is important to note that once the initial pressure has been lowered past the limit in the smooth tube [14], it is necessary to extend the rough section all the way to the driver. For initial pressures near the limit (1.75 kPa), the detonation velocity is reduced upon entering the rough section. There is a slow decay in velocity until a steady velocity is obtained. However no galloping detonation is observed near the limits as in smooth tubes. Regardless of mixture, tube diameter $D$ or roughness $\delta/D$, no galloping detonation was observed in the present study.

An averaged velocity for the propagation in the rough section can also be obtained from the averaged slope of the trajectory over the length of the test tube. This value of velocity is similar to the averaged local velocity obtained from adjacent photodiode signals. The averaged velocity, obtained by the slope of the trajectory, is non-dimensionalized by $V_{CJ}$ to allow for comparison between different mixtures and initial pressures. The detonation velocity in smooth tubes as the limit is approached has been studied by Gao et al. [14] and the results are also shown as comparison to the present results.

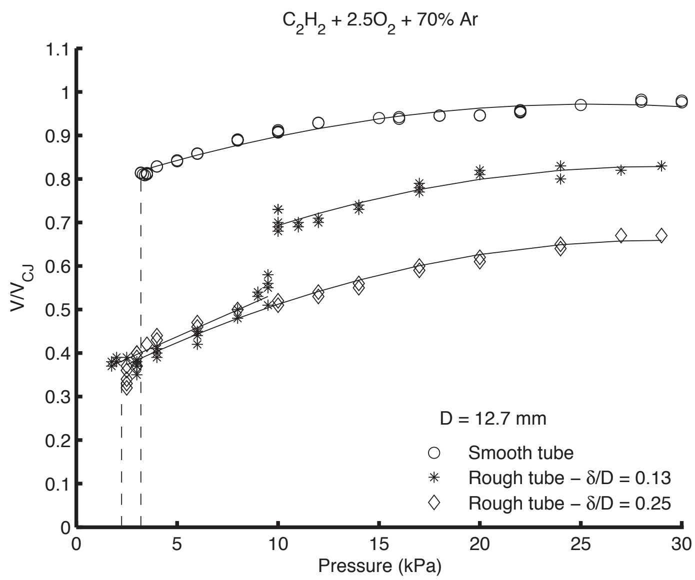


Figure 3–3: $V/V_{CJ}$ vs. Pressure for $C_2H_2 + 2.5O_2$ + 70% Ar in the 12.7 mm diameter tube

Fig. 3–3 shows the averaged velocity ($V/V_{CJ}$) as the initial pressure is decreased towards the limits for $C_2H_2$ + $2.5O_2$ + 70% Ar . The tube diameter is 12.7 mm and two degrees of roughness $\delta/D$ = 0.13 and 0.25 are shown.

For $\delta/D$ = 0.13, the detonation velocity far from the limit is about 85% $V_{CJ}$ and decreases continuously as the limit is approached. An abrupt drop in velocity is observed at an initial pressure of 9.5 kPa. After the drop, the velocity continues to decrease slowly. The velocity at the limit is found to be about 40% $V_{CJ}$. For $\delta/D$ = 0.25, the detonation velocity far from the limit is about 70% $V_{CJ}$ and continuously decreases towards the limit. The velocity at the limit is about 35% $V_{CJ}$. The limiting pressure for both degrees of roughness is found to be about 2 kPa. Also shown for comparison are the results for a smooth tube of 12.7 mm diameter [14]. The limit occurs at 3.2 kPa and the velocity for the smooth tube is about

80% $V_{CJ}$.

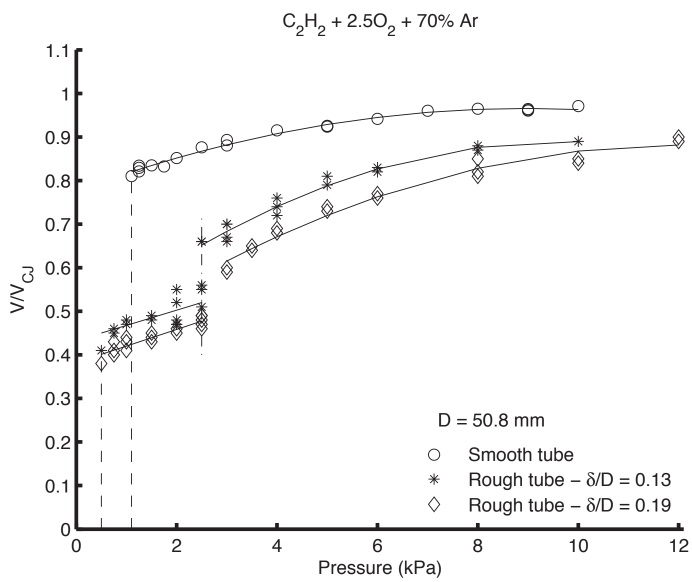


Figure 3–4: $V/V_{CJ}$ vs. Pressure for $C_2H_2 + 2.5O_2 + 70\%$ Ar in the 50.8 mm diameter tube

Fig. 3–4 shows the averaged velocity as the initial pressure is decreased towards the limits for $C_2H_2 + 2.5O_2 + 70\%$ Ar and a tube diameter of 50.8 mm. Two degrees of roughness $\delta/D$ = 0.13 and 0.19 are shown.

For $\delta/D$ = 0.13, the detonation velocity far from the limit is about 90% $V_{CJ}$ and decreases continuously towards the limit. An abrupt drop in velocity occurs at an initial pressure of 2.5 kPa. For $\delta/D$ = 0.19, the detonation velocity behaviour is similar to that of $\delta/D$ = 0.13. The velocity for $\delta/D$ = 0.19 is slightly lower for the range of initial pressures and the abrupt drop is observed at the same initial pressure. The limit for both degrees of roughness is found to occur at about 0.5 kPa and the detonation velocity is about 40%

$V_{CJ}$. The results for a smooth tube of 50.8 mm diameter [14] are shown for comparison. The limit is found to be at 1.1 kPa and the detonation velocity is about 80% $V_{CJ}$.

As shown in Fig. 3–3 and Fig. 3–4, 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 $\delta/D$, the effect of tube diameter $D$ on the velocity is small. For $\delta/D \leq 0.19$, there is a similar velocity behaviour 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. Thus the roughness is found to always extend the detonation limits.

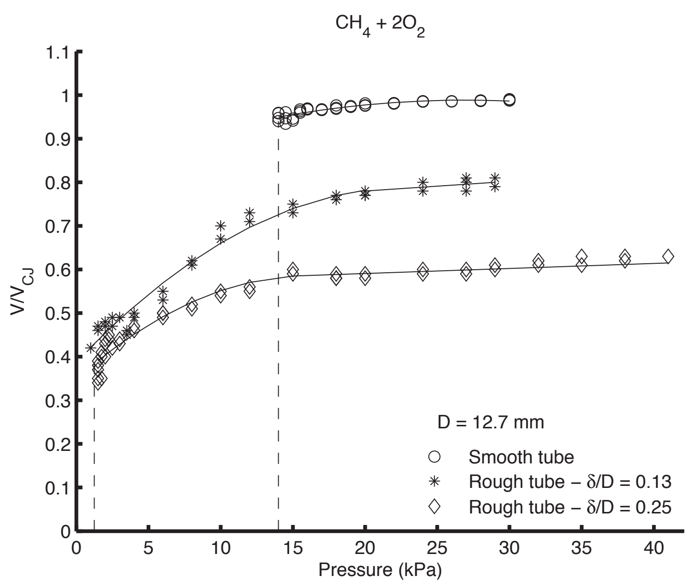


Figure 3–5: $V/V_{CJ}$ vs. Pressure for $CH_4$ + $2O_2$ in the 12.7 mm diameter tube

Fig. 3–5 shows the averaged velocity as the initial pressure is decreased towards the limits for an “unstable” mixture of $CH_4$ + $2O_2$ . The tube diameter is 12.7 mm and two degrees of roughness $\delta/D$ = 0.13 and 0.25 are shown.

For $\delta/D$ = 0.13, the detonation velocity far from the limit is about 80% $V_{CJ}$ and decreases to about 40% $V_{CJ}$ at the limit. For $\delta/D$ = 0.25, the detonation velocity is about 65% $V_{CJ}$ far from the limit. The velocity at the limit is about 35% $V_{CJ}$. The limiting pressure for both degrees of roughness is found to occur at about 1.25 kPa. The results for a smooth tube are so shown for comparison [14]. The limit is found to occur at 14 kPa and the detonation velocity is about 94% $V_{CJ}$.

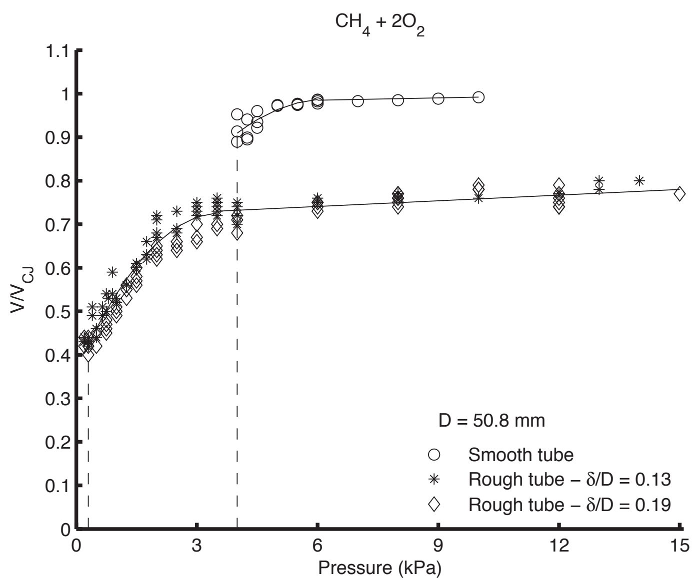


Figure 3–6: $V/V_{CJ}$ vs. Pressure for $CH_4$ + $2O_2$ in the 50.8 mm diameter tube

Fig. 3–6 shows the averaged velocity as the initial pressure is decreased towards the limits for $CH_4$ + $2O_2$ . The tube diameter is 50.8 mm and two degrees of roughness $\delta/D$ = 0.13 and 0.19 are shown.

For both $\delta/D$ = 0.13 and 0.19, the detonation velocity is about 80% $V_{CJ}$ far from the limit. The limit for both degrees of roughness is found to be about 0.2 kPa at 40% $V_{CJ}$. Also shown for comparison are the results for a smooth tube [14]. The limit is found to occur at 4 kPa and the velocity is about 91% $V_{CJ}$.

As shown in Fig. 3–5 and Fig. 3–6, the velocity of the detonation remains relatively constant, decreasing slowly as the limiting pressure is approached. Near the limit, the velocity decreases at a faster rate until the limit is found. The velocity in the rough tube at a given pressure is always lower than that of the smooth tube. For a given $\delta/D$ , the effect of tube diameter $D$ is small. For $\delta/D \leq$ 0.19, there is a similar velocity behaviour 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. Thus roughness is found to extend the propagation limits.

The sensitivity of a mixture is varied via the initial pressure, however in order to compare the sensitivities for two different mixtures the cell size "$\lambda$" is a more appropriate parameter. The cell size for $C_2H_2$ + $2.5O_2$ + 70% Ar is given by Gao et al. [17] and for $CH_4$ + $2O_2$ is found from the CALTECH detonation database [18]. The physical scale of the tube is characterized by the see-through diameter $d = D - 2\delta$, where $D$ is tube diameter and $\delta$ is wire diameter. Thus "$d$" represents the central core diameter of the rough tube. A non-dimensional factor of physical scale "$d$" to chemical scale "$\lambda$" is now used in order to further illustrate how the behaviour of the detonation velocity is tube diameter independent. The comparison to results in the smooth tube [14] are again important in understanding the detonation limit in rough tubes. Note for the smooth tube, the physical scale is represented by $d = D$. The behaviour of detonation velocity with varying $d/\lambda$ is observed.

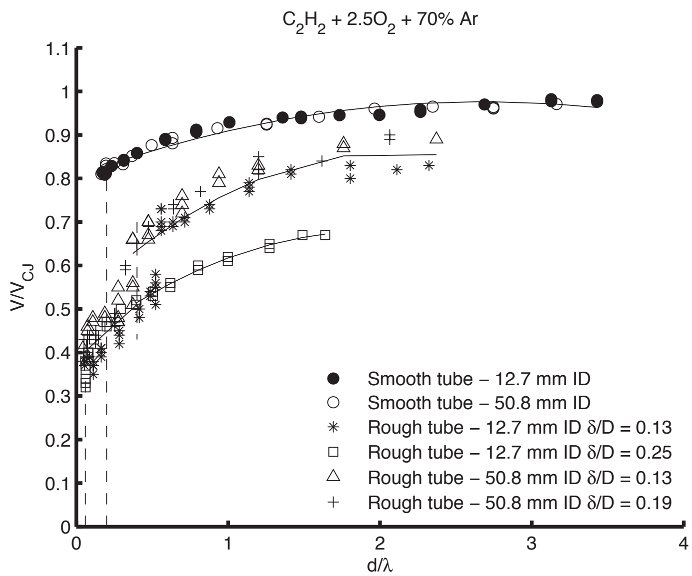


Figure 3–7: $V/V_{CJ}$ vs. $d/\lambda$ for $C_2H_2$ + 2.5$O_2$ + 70% Ar

Fig. 3–7 shows the velocity with the ratio $d/\lambda$ for $C_2H_2$ + 2.5$O_2$ + 70% Ar . The velocity behaviour for $C_2H_2$ + 2.5$O_2$ + 70% Ar and $\delta/D \leq 0.19$ show that there is a similar behaviour for different tube diameters. The velocity is about 85% $V_{CJ}$ far from the limit and continuously decreases towards the limit (decreasing $\delta/\lambda$). An abrupt drop in velocity occurs at $d/\lambda \cong 0.4$. Subsequent to the drop, further decrease in $d/\lambda$ indicate further decrease in detonation velocity. The velocity at the limit is about 40% $V_{CJ}$. A similar drop in velocity was observed in the experiments of Peraldi et al. [6] and Knystautas et al. [7]. The jump from a so-called quasi-detonation to wave at isobaric sound speed occurred at

$d/\lambda \cong 1$ for stable mixtures. The difference in $d/\lambda$ values could be due to the large variation in cell size ($\lambda$) measurements. It could also take into account the difference between the roughness used in this study (Shchelkin spiral) and the obstacles used in past studies (orifice plates). The geometry of the orifice plate is straight forward, a diameter $d$ can be easily defined to be used in the $d/\lambda$ correlation. For the Shchelkin spiral, the geometry is very different making it more difficult to define the diameter $d$ to compare the $d/\lambda$ relation to that of an orifice plate.

For $\delta/D$ = 0.25, the velocity is found to be about 70% $V_{CJ}$ far from the limit, and decreases slowly to about 35% $V_{CJ}$ when failure occurs. At the limit, the average value of $d/\lambda$ for all tube diameters and roughness $\delta/D$ is $d/\lambda \cong$ 0.05.

The behaviour of the velocity in the smooth tube is similar for different tube diameters. The velocity is about 95% $V_{CJ}$ far from the limit and decreases slowly to about 80% $V_{CJ}$ when failure occurs abruptly. At the limit, $d/\lambda \cong$ 0.17.

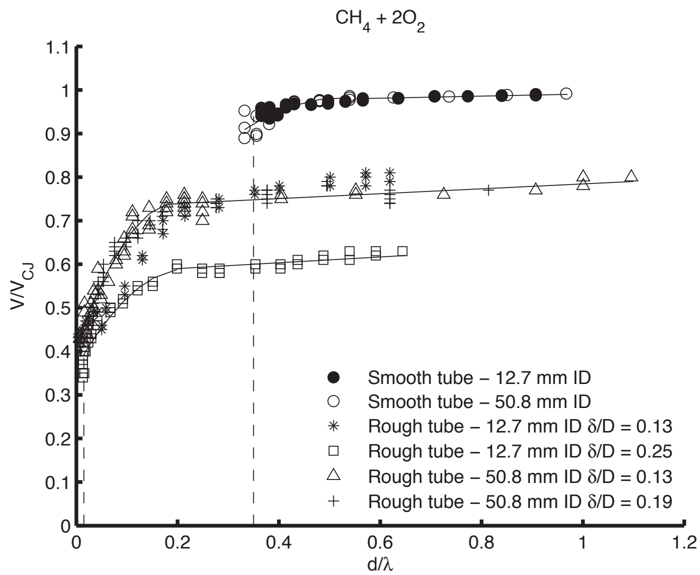


Figure 3–8: $V/V_{CJ}$ vs. $d/\lambda$ for $CH_4$ + $2O_2$

Fig. 3–8 shows the dimensionless velocity with the ratio $d/\lambda$ for $CH_4$ + $2O_2$ . The velocity behaviour for $CH_4$ + $2O_2$ and $\delta/D \leq 0.19$ show that there is a similar behaviour for different tube diameters. The velocity far from the limit is about 80% $V_{CJ}$. The velocity at the limit is about 40% $V_{CJ}$. For $\delta/D$ = 0.25, the velocity is much lower, dropping from 65% $V_{CJ}$ to 35% $V_{CJ}$. At the rough limit, the average value of $d/\lambda$ all tube diameters and roughness $\delta/D$ is $d/\lambda \cong$ 0.009.

The velocity behaviour in the smooth tube is similar regardless of tube diameter. The velocity is about 98% $V_{CJ}$ far from the limit and decreases slowly to about 93% $V_{CJ}$ when failure occurs abruptly. At the limit, $d/\lambda \cong$ 0.35.

Table 3–1 summarizes the average values of $d/\lambda$ at the limits for the two mixtures. From the results shown in Fig. 3–7, Fig. 3–8 and Table 3–1, wall roughness tends to extend the limit beyond that of the smooth tubes. For the unstable $CH_4$ + $2O_2$ mixture, it is observed that the wall roughness is much more effective in prolonging the propagation of the detonation wave than for the stable $C_2H_2$ + $2.5O_2$ + 70% Ar mixture. The effects of tube diameter are negligible, but rather the degree of roughness $\delta/D$ has a greater influence on the velocity behaviour.

Table 3–1: Average values of $d/\lambda$ at the limits

| Mixture | $d/\lambda_{smooth}$ | $d/\lambda_{rough}$ |
|---|---|---|
| $C_2H_2$ + $2.5O_2$ + 70% Ar | 0.17 | 0.05 |
| $CH_4$ + $2O_2$ | 0.35 | 0.009 |

While it is clear that the roughness tends to extend the limit, there is also an interesting velocity behaviour for the different degrees of roughness. Regardless of mixture and tube diameter, for a given mixture and for $\delta/D \leq 0.19$, the velocity behaviour of the detonation is similar both far from the limit and at the limiting pressure . For $\delta/D$ = 0.25, the velocity was lower (about 15% $V_{CJ}$) far from the limit, but quite similar at the limit. The velocity at the limit was always found to be about 40% $V_{CJ}$ for all mixture, tube diameter and roughness combinations.

The detonation velocity does not provide any information on the structure of the detonation front. Thus smoked foils are used to observe the detonation structure as the limits are approached.

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 produces turbulence as well which can be considered artificially generated instability. In both cases, the turbulence aids in the propagation of the detonation wave.

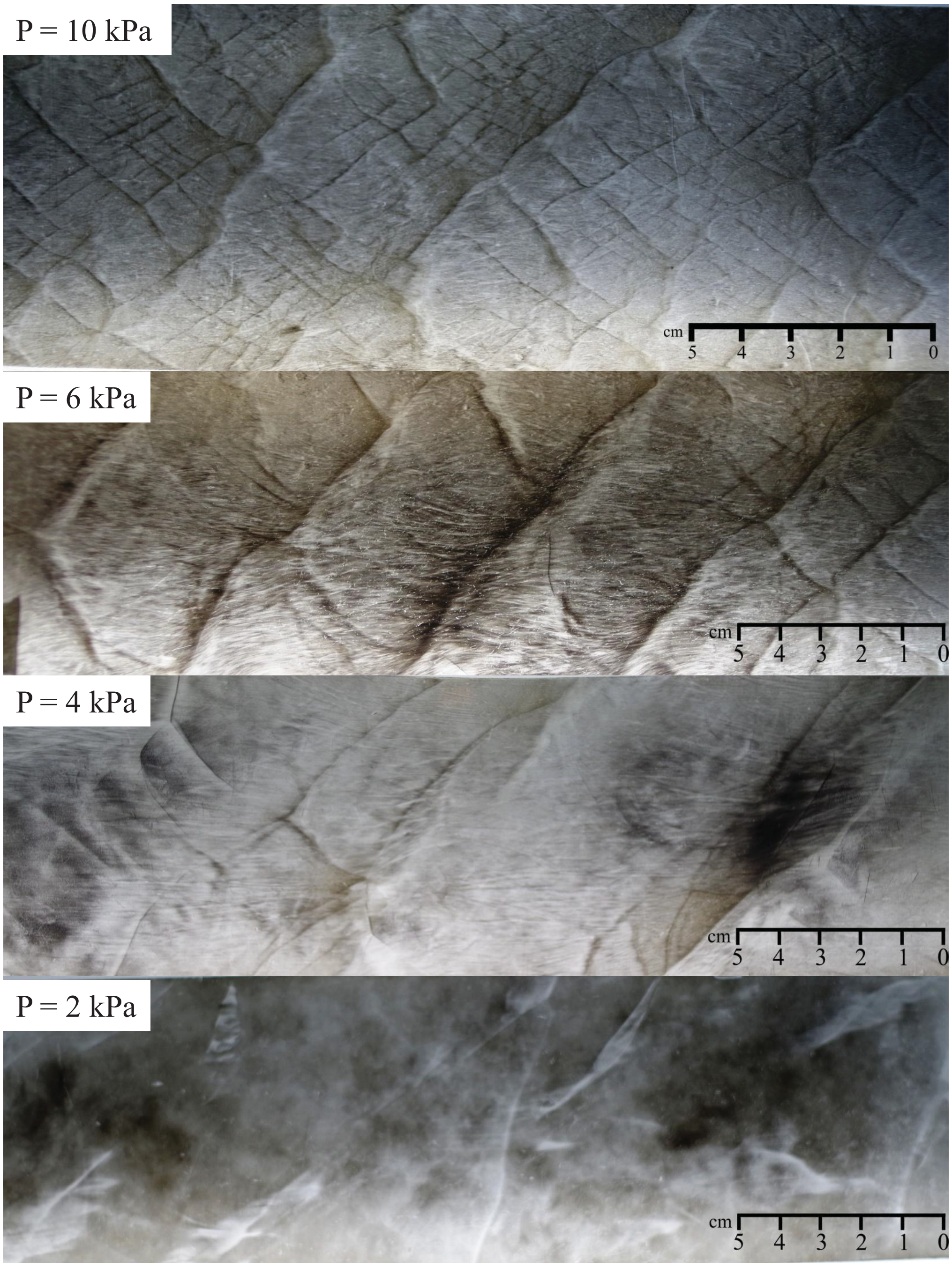


Figure 3–9: Smoked foils for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 50.8 mm diameter tube with $\delta/D = 0.13$

Typical smoked foils for the $C_2H_2$ + $2.5O_2$ + 70% Ar mixture with the $\delta/D$ = 0.13 are shown in Fig. 3–9. For this mixture in the rough tubes, the smoked foils are similar regardless of the degree of roughness. A multi-cellular structure is observed at pressures far from the limit. As the pressure is lowered, the cells become larger in size and the structure is now a double-head spin. When pressure is decreased further, the single-head spin structure appears, indicating the lowest mode of instability. Note that the single-head spin is last recorded just prior to the abrupt drop in velocity. Thus the loss of single-head spin creates the large velocity deficit observed previously in Fig. 3–4. Once the single-head spin is lost, the only traces on the smoked foil are random and weak which are due to the perturbations from the spiral. Below this pressure, nothing is picked up on the smoked foil. Thus at the limiting pressure in the rough tube, there is no cellular structure.

It is interesting to note that for $C_2H_2$ + $2.5O_2$ + 70% Ar in the smooth tube the loss of single-head spin corresponds to the limiting pressure [14]. In the rough tube, the loss of single-head spin corresponds the loss of the self-generated instability of the mixture. Since the detonation front of the stable $C_2H_2$ + $2.5O_2$ + 70% Ar mixture is not very affected by the roughness (artificially generated instability), the loss of the single-head spin corresponds to an abrupt drop in velocity, as seen in Fig. 3–4.

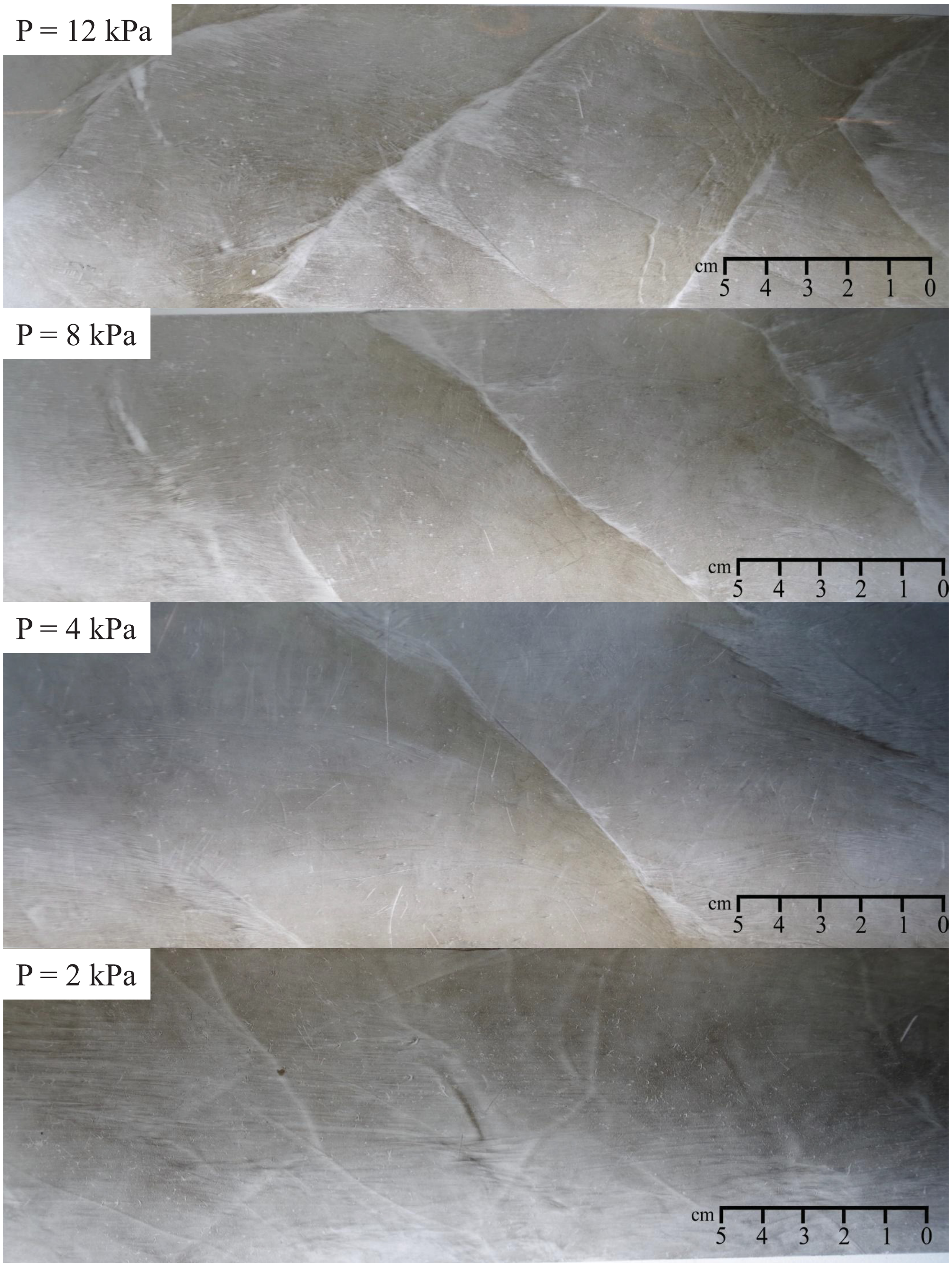


Figure 3–10: Smoked foils for $CH_4$ + $2O_2$ in the 50.8 mm diameter tube with $\delta/D$ = 0.19

Typical smoked foils for the $CH_4 + 2O_2$ mixture with the $\delta/D = 0.19$ are shown in Fig. 3–10. For this mixture in the rough tubes, the smoked foils are similar regardless of the degree of roughness. A double-head spin with very large cells is observed at pressures far from the limit. As the pressure is lowered, a single-head spin structure is now observed. When pressure is decreased further, the single-head spin structure appears weaker until it is lost completely. Once the single-head spin is lost, the only traces on the smoked foil are random and weak which are due to the perturbations from the spiral. Below this pressure, nothing is picked up on the smoked foil. Thus at the limiting pressure in the rough tube, there is no cellular structure.

It is interesting to note that for $CH_4 + 2O_2$ in the smooth tube, the loss of single-head spin corresponds to the limiting pressure [14]. In the rough tube, the loss of single-head spin corresponds to the loss of the self-generated instability of the mixture. The detonation front of the unstable $CH_4 + 2O_2$ mixture is affected by the roughness (artificially generated instability) for the range of pressures. Once the single-head spin is lost, no change in velocity is observed since the artificial instability played a role in the detonation structure at higher pressures as well.

The smoked foils showed that no structure was recorded at the limiting pressure, regardless of the mixture. Once the single-head spin is lost, the detonation continues to propagate due to the roughness of the tube and the artificially generated transverse waves.

The limiting pressure in rough tubes was determined using velocity measurements. The velocity at the limit was determined to be about 40% $V_{CJ}$. The smoked foils show no cellular structure at the limit. This holds true for all mixture, tube diameter and degrees of roughness.

# CHAPTER 4
# Conclusion

The present results indicate that in rough tubes, detonation velocity can vary continuously from close to the theoretical Chapman-Jouguet value (as in smooth tubes) far from the limits to about 40% $V_{CJ}$ where the detonation fails. This is in contrast to the detonations in smooth tubes, where the detonation velocity seldom decreases to less than 80% $V_{CJ}$ at the limits. There is strong evidence that wall roughness tends to facilitate the self-sustained propagation of detonation waves. It has been already established that wall roughness facilitates the transition from deflagration to detonation. The mechanism in promoting detonation propagation is due to the turbulence generated by the rough wall. The detonation structure in a rough tube is not unlike the reaction zone of a cellular detonation where pressure waves and velocity fluctuations arise from the intrinsic instability of the detonation front. Thus wall roughness promotes the generation of pressure and vorticity fluctuations and hence extends the detonation limits of smooth tubes where turbulence can only arise from the instability of the detonation front. The smoked foil records indicate that in rough tubes, the cellular instability of the detonation still occurs in the core away from the roughness near the wall. However, when conditions are such that when the natural instability cannot be sustained, turbulence generated by the walls takes over and maintains self-propagation of the detonation.

## APPENDIX A
## Appendix A - All Figures

### Trajectories - Far from Limit

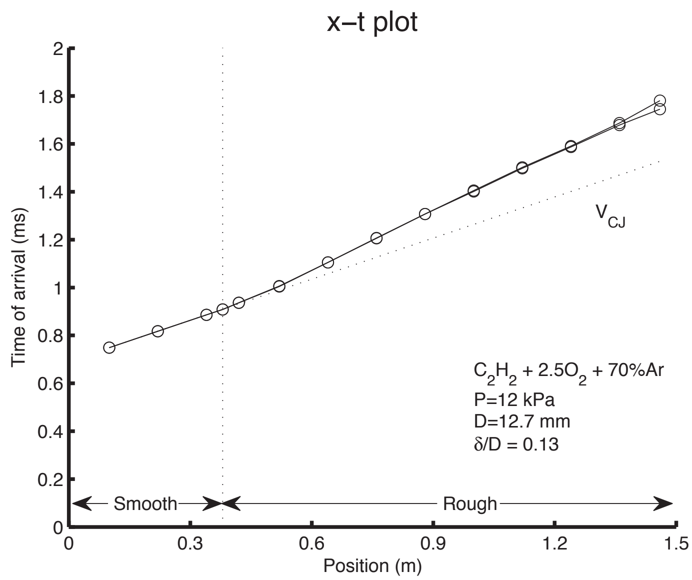


Figure A–1: Detonation Trajectory for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 12.7 mm tube with $\delta/D$ = 0.13 at a pressure of 12 kPa

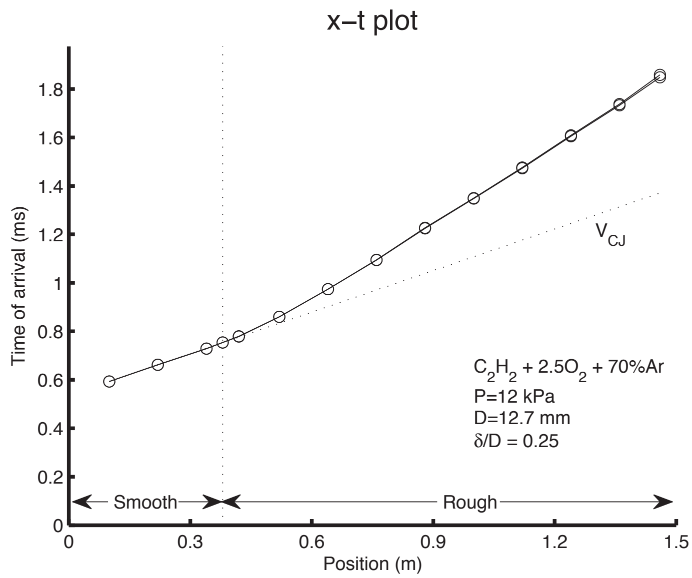


Figure A–2: Detonation Trajectory for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 12.7 mm tube with $\delta/D$ = 0.25 at a pressure of 12 kPa

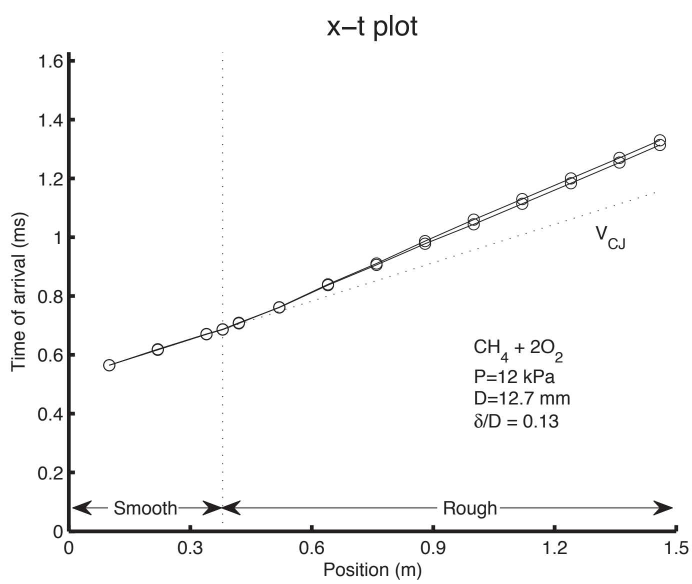


Figure A–3: Detonation Trajectory for $CH_4$ + $2O_2$ in the 12.7 mm tube with $\delta/D$ = 0.13 at a pressure of 12 kPa

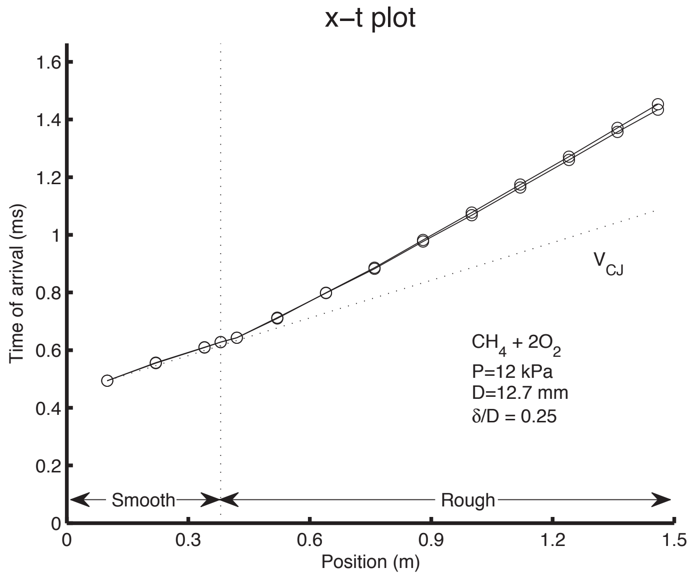


Figure A–4: Detonation Trajectory for $CH_4 + 2O_2$ in the 12.7 mm tube with $\delta/D = 0.25$ at a pressure of 12 kPa

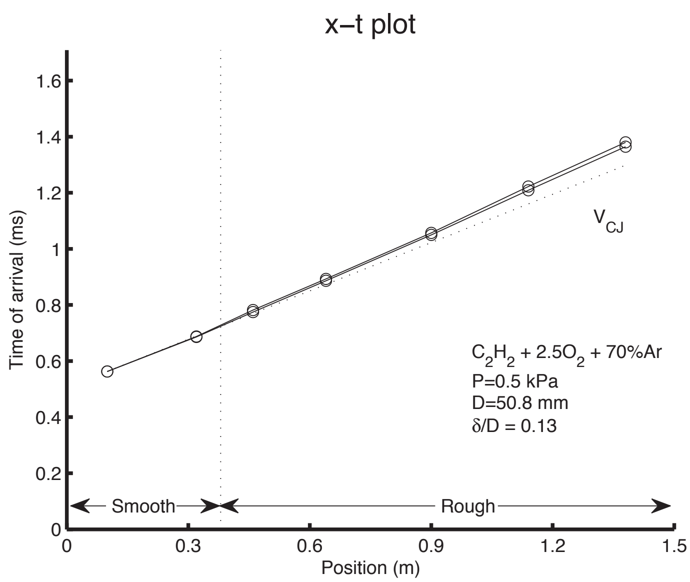


Figure A–5: Detonation Trajectory for $C_2H_2 + 2.5O_2$ + 70% Ar in the 50.8 mm tube with $\delta/D = 0.13$ at a pressure of 12 kPa

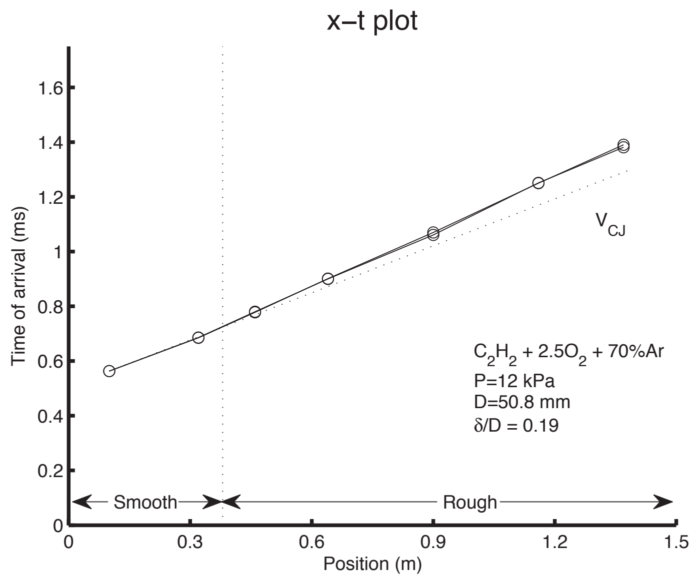


Figure A–6: Detonation Trajectory for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 50.8 mm tube with $\delta/D$ = 0.19 at a pressure of 12 kPa

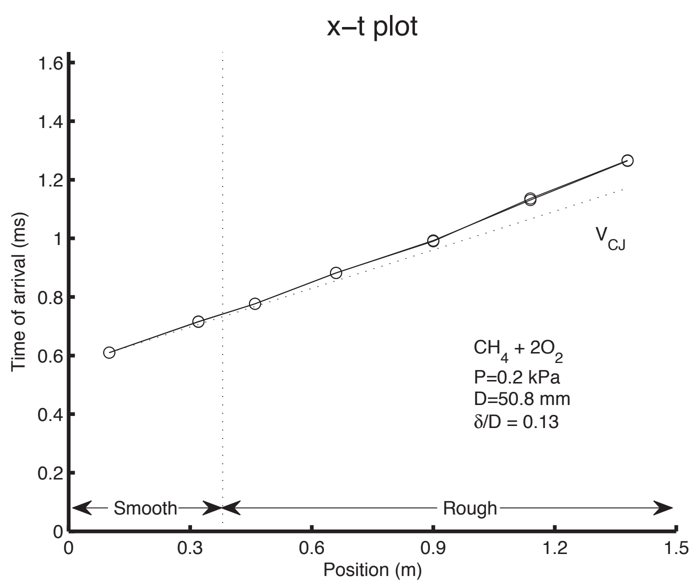


Figure A–7: Detonation Trajectory for $CH_4$ + $2O_2$ in the 50.8 mm tube with $\delta/D$ = 0.13 at a pressure of 12 kPa

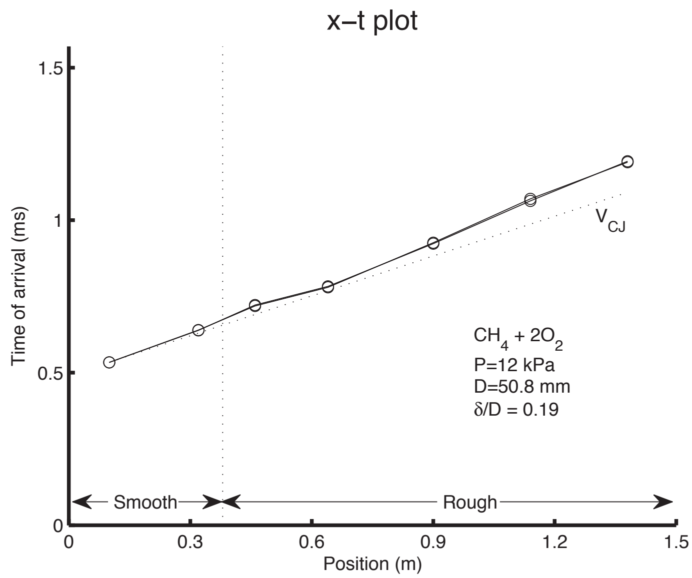


Figure A–8: Detonation Trajectory for $CH_4$ + $2O_2$ in the 50.8 mm tube with $\delta/D$ = 0.19 at a pressure of 12 kPa

**Trajectories - Near the Limit**

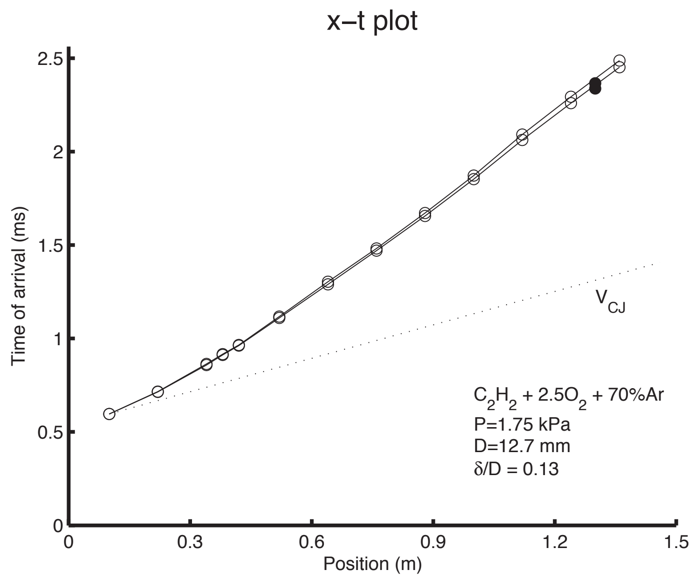


Figure A–9: Detonation Trajectory for $C_2H_2$ + 2.5$O_2$ + 70% Ar in the 12.7 mm tube with $\delta/D$ = 0.13 at the limit pressure of 1.75 kPa

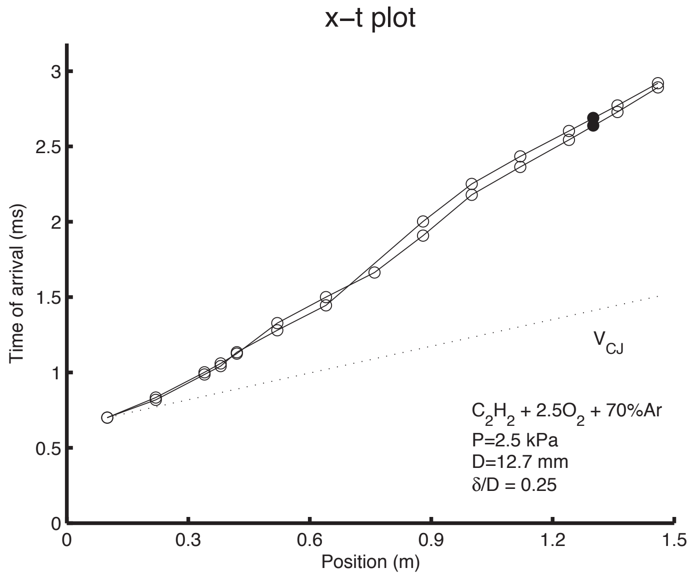


Figure A–10: Detonation Trajectory for $C_2H_2$ + 2.5$O_2$ + 70% Ar in the 12.7 mm tube with $\delta/D$ = 0.25 at the limit pressure of 2.5 kPa

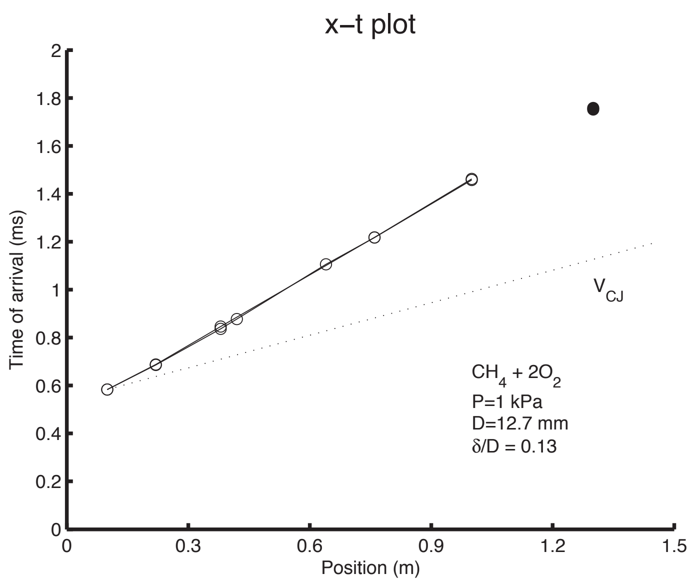


Figure A–11: Detonation Trajectory for $CH_4$ + 2$O_2$ in the 12.7 mm tube with $\delta/D$ = 0.13 at the limit pressure of 1 kPa

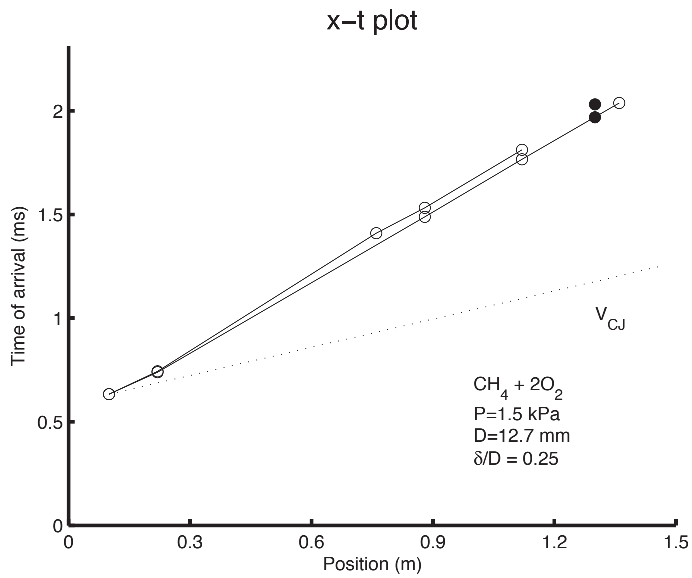


Figure A–12: Detonation Trajectory for $CH_4$ + $2O_2$ in the 12.7 mm tube with $\delta/D$ = 0.25 at the limit pressure of 1.5 kPa

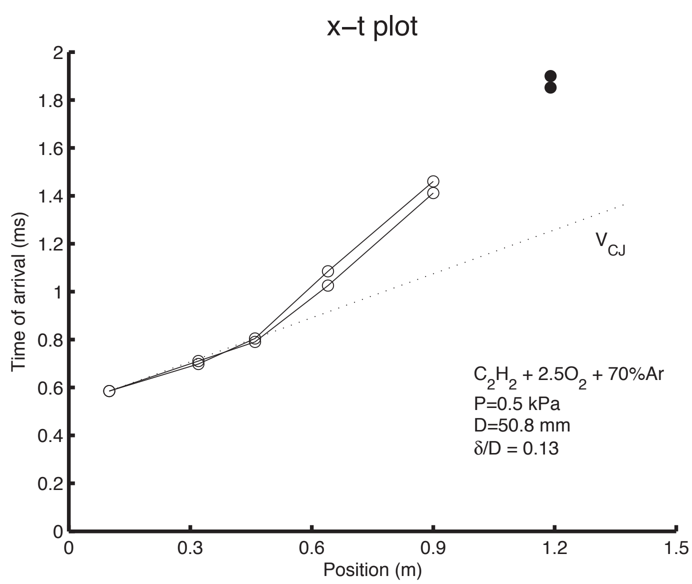


Figure A–13: Detonation Trajectory for $C_2H_2$ + $2.5O_2$ + 70% Ar in the 50.8 mm tube with $\delta/D$ = 0.13 at the limit pressure of 0.5 kPa

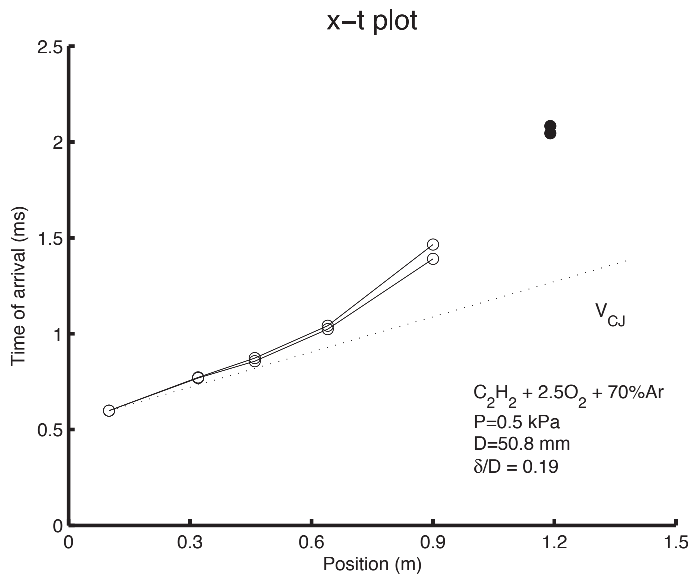


Figure A–14: Detonation Trajectory for $C_2H_2$ + 2.5$O_2$ + 70% Ar in the 50.8 mm tube with $\delta/D$ = 0.19 at the limit pressure of 0.5 kPa

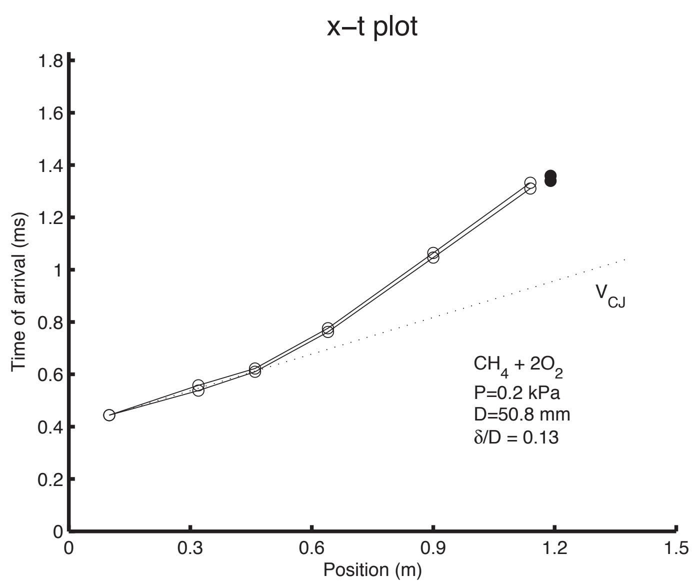


Figure A–15: Detonation Trajectory for $CH_4$ + 2$O_2$ in the 50.8 mm tube with $\delta/D$ = 0.13 at the limit pressure of 0.2 kPa

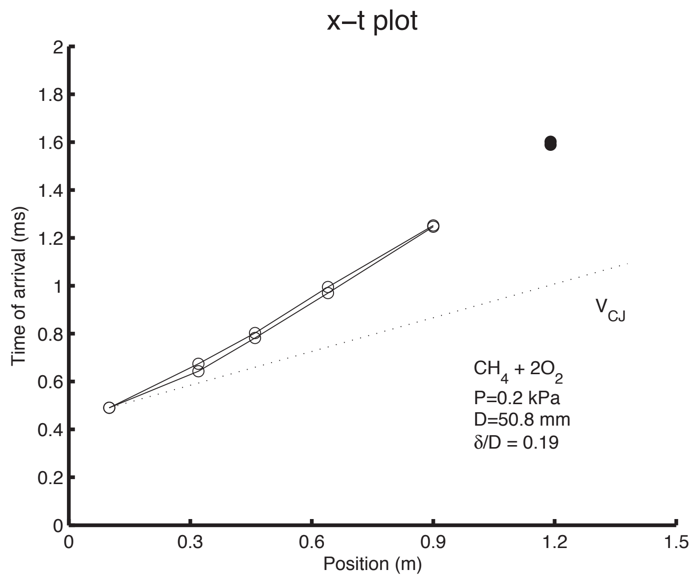


Figure A–16: Detonation Trajectory for $CH_4$ + $2O_2$ in the 50.8 mm tube with $\delta/D$ = 0.19 at the limit pressure of 0.2 kPa

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