Fuel 286 (2021) 119384

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Investigation of near-limit detonation propagation in a tube with helical spiral

Yuanyi Liu [a,b], John H.S. Lee [b,*], Houzhang Tan [a], Hoi Dick Ng [c]

[a] MOE Key Laboratory of Thermo-Fluid Science and Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[b] Department of Mechanical Engineering, McGill University, Montreal, QC H3A 0C3, Canada
[c] Department of Mechanical, Industrial and Aerospace Engineering, Concordia University, Montreal, QC H3G 1M8, Canada

ARTICLE INFO

Keywords:
Detonation
Limits
Rough-walled tube
Cellular structure
Velocity deficit

ABSTRACT

The present study investigated the effect of wall roughness on the velocity, cellular structure, and limits of detonation propagation in tubes. Wall roughness was effected by placing a wire spring into the tube. Since the wire diameter is small compared to the tube diameter, the wire spiral is more representative of wall roughness than the repeated orifice plates used in the majority of previous studies. Detonation velocity was determined from the time-of-arrival of ionization probes spaced along the tube. Smoked foils were also inserted into the smooth section of the tube as well as immediately downstream of the rough section to record the cellular structure of the detonation wave. Premixed mixtures of $C_2H_2 + 2.5O_2 + 70\%Ar$ and $C_2H_2 + 5N_2O$ were used, which represent weakly unstable and unstable detonations, respectively. The initial pressure ranges of the experiments varied from 16 kPa (well within the detonation limits) to a few kPa at the limits. The present study indicates that wall roughness increases the velocity deficit, increases the cell size, as well as rendering the cellular structure more irregular. Wall roughness is also found to narrow the detonation limits in contrast to the conclusion of the previous studies.

1. Introduction

Detonation limits refer to conditions outside of which a propagating detonation cannot be sustained [1]. These are a function of explosive mixture composition, initial pressure and temperature, as well as boundary conditions such as tube diameter and wall roughness as investigated in this study. Numerous investigations have been carried out in the past few decades on detonation limits in smooth tubes [2–9]. In general, when limits are approached, the detonation velocity deficit increases and the unstable cellular structure is driven to lower unstable modes, i.e., from a multi-headed structure to a single-headed spin. At the limits, a spectrum of unstable phenomena can generally be observed where the combustion wave propagation becomes increasingly unsteady accompanying by large velocity fluctuations [10–13]. The limit phenomenon is complex, involving losses and the effects of instability. To this end, this paper investigates how the wall roughness influences the behavior of the detonation velocity and the cellular detonation structure near the limits.

The majority of the previous studies on so-called "rough tubes" are based on the use of repeated orifice plate obstacles [14–22] where the dimensions of the orifice diameter and spacing are of the order of the tube diameter itself. Thus the roughness (as defined by the difference between the tube and the orifice diameter) is quite significant as compared to the tube diameter, i.e., $d/D \sim O(1)$. For propagation past an orifice plate, diffraction and re-initiation via reflection off the obstacle and tube wall by the diffracted shock play the controlling role on the detonation propagation.

The present study uses wire spirals to produce the wall roughness. The wire diameter of the spiral is small compared to the tube diameter, i.e., $\delta/D \ll 1$. Hence, this arrangement can be considered more like wall roughness than the use of orifice plates. On another note, most previous studies [23–28] in rough tubes are concerned with promoting flame acceleration and transition from deflagration to detonation. There are relatively few studies of detonation propagation in tubes with wire spirals. Guénoche [29] measured detonation velocity in $C_2H_2 + O_2$ in a tube with different wire spirals. Manson et al. [30] used streak schlieren to observed the influence of the wire spiral on the detonation structure in propane-oxygen mixture with different degrees of nitrogen dilution. They observed that wall roughness tends to change a multi-headed detonation to a lower unstable mode (e.g., spinning detonation).

* Corresponding author at: Department of Mechanical Engineering, McGill University, 817 Rue Sherbrooke Ouest, Montreal, QC H3A 0C3, Canada
E-mail address: john.lee@mcgill.ca (J.H.S. Lee).

https://doi.org/10.1016/j.fuel.2020.119384
Received 10 July 2020; Received in revised form 22 September 2020; Accepted 30 September 2020
Available online 17 October 2020

Recently, Zhang [31] investigated the detonation propagation velocity behavior and cellular structure of stoichiometric hydrogen–oxygen mixture in spiral obstacles with different degrees of roughness. Other recent studies such as those by Starr et al. [32], Zhang et al. [33] and Li et al. [34] observed that wall roughness tends to widen the detonation limits. This conclusion that terms limits is based on complete failure of the detonation wave as the limit. A proper definition of limits is introduced here by the absence of any cellular detonation structure.

After all, there is a need to obtain more information on the propagation of detonation in rough walled tubes, in particular, the influence of wall roughness on the propagation velocity, structure, and the limits. Intuitively, the wall roughness can have a competing effect on the detonation propagation. On one hand, the wall roughness can either generate turbulent fluctuation which could be beneficial for unstable detonation propagation. On the other hand, losses due to wall roughness in tubes can promote detonation failure. Therefore, in the present study we carried out experiments using both weakly unstable (with regular cell pattern) and highly unstable (with irregular cellular pattern) mixtures. In addition to velocity measurements, we also measured the detonation structure using smoked foils and determine the detonation limits based on the absence of cellular structure in the wave.

2. Experimental details

The experiments were carried out in a plastic tube 50.8 mm in inner diameter and 4.5 m in length. Premixed mixture of $C_2H_2 + 2.5O_2 + 70\%$ Ar as well as a more unstable mixture of $C_2H_2 + 5N_2O$ were used in the present study. Ignition was via a high-energy spark from a low inductance capacitor discharge. To ensure rapid formation of the detonation wave, a short length of Shchelkin spiral was also placed at the ignition end. For the very low pressure experiments when it was difficult to initiate the detonation with just the spark alone, a small amount of a more sensitive $C_2H_2 + O_2$ mixture was introduced into the tube at the ignition end near the igniter as a driver. The volume of the driver mixture ($C_2H_2 + O_2$) used was very small: just enough to ensure detonation initiation. There was a small degree of mixing as the driver mixture was introduced into the tube. Therefore, there was a gradient of mixture composition near the ignition end of the tube. Nevertheless, the mixture in the remainder of the tube was the test mixture. A Chapman-Jouguet (CJ) detonation was obtained downstream of the Shchelkin spiral at the ignition end. This was confirmed by velocity measurements as well as from a smoked foil placed in the smooth section before the rough spiral section. The detonation cell size observed was found to correspond to that of the CJ detonation of the mixtures used. A schematic of the experimental arrangement is shown in Fig. 1.

The wall roughness was obtained by inserting a long length of wire spiral (Music Wire ASTM A228) into the tube. The outer diameter of the wire spiral was slightly smaller than the inner diameter of the detonation tube just to permit easy insertion of the spiral into the tube. Drops of epoxy were also used to ensure that the spiral was kept stationary as the detonation propagated in the spiral section. The dimension of the various spirals used in the present study and the corresponding characteristic parameters are also shown in Table 1.

The ionization probes used to register the combustion wave time-of-arrival were constructed by inserting two steel needles into a ceramic thermocouple tube of 3.2 mm outer diameter. The probe spacing was 150 mm apart along the tube. From the ionization probes, the combustion wave trajectory was obtained and the local velocity can be determined. At least three experiment runs were carried out at the same condition to obtain the shot-to-shot reproducibility and also to observe any unsteady variation.

Smoked foils were coiled up and then inserted in the smooth section just prior to the rough section. Another foil was also placed immediately downstream of the rough section to register the structure in the rough section. The smoked foil arrangement is illustrated in Fig. 2. Smoked foil "A" recorded the initial cellular structure prior to the detonation entering the rough section and smoked foil "B" recorded the structure when the detonation exits the rough section. Note that when a smoked foil is inserted into the spiral section, the wall roughness will be covered by the foil and hence, one essentially has a smooth tube. Note that inserting the foil into the rough section or placing the foil immediately downstream of the spiral section amount to the same thing. We have carried out experiments for both arrangements and obtained the same result. Thus, we just positioned the foil downstream of the spiral in the present experiment. We also carried out a few experiments with a foil that cover only half the tube circumference. The foil in this case indicated the same cellular characteristics. Thus, we abandoned this more tedious experiment and just placed the foil downstream of the spiral.

3. Results and discussion

The variation of the detonation velocity with distance was obtained for different roughness parameters (i.e., σ and φ) and different initial pressures P_0. For characterizing surface roughness, there exist many different parameters in use. Given the way how the wall roughness is generated in this work using the wire spiral and also for simplicity, σ and φ are defined as δ/D_t and l/D_t, respectively, where δ is the wire diameter and l is the pitch of the spiral. Using these parameters, the wall

Table 1
Spiral parameters.

Wire diameter, δ [mm]	Pitch, l [mm]	σ, (δ/D_t)	φ, (l/D_t)
1.5	3.4	0.03	0.07
3	6.5	0.06	0.13
6.5	14	0.13	0.27

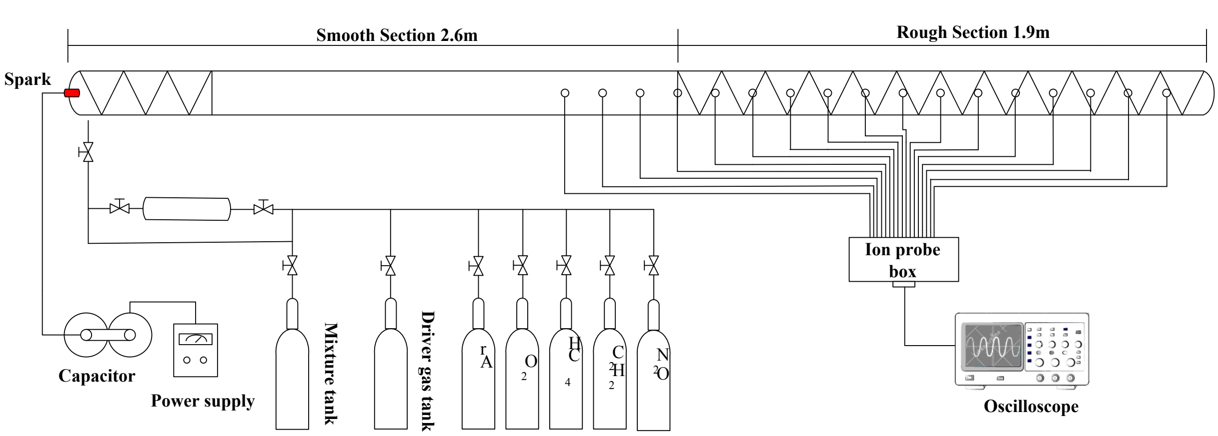

Fig. 1. A schematic of the experiment setup.

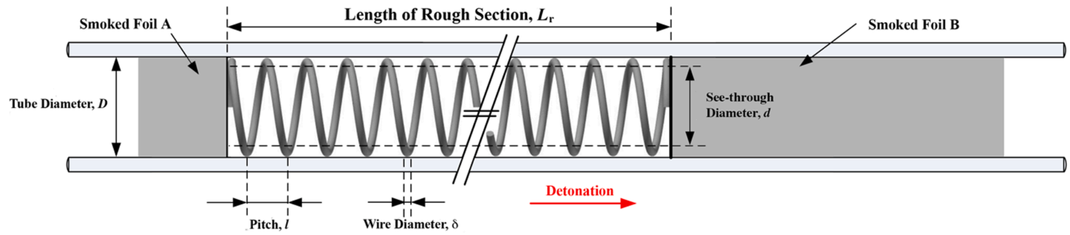

Fig. 2. A sketch of the wire spiral and locations of the smoked foils in the test section.

roughness is thus quantified separately in both the amplitude and spacing. It is worth noting that another way to define roughness is provided in [31,33] where these two ratios were essentially combined into a single parameter δ/l. Also, most of recent works vary mainly δ/D_t of the spiral for different roughness degree while keeping the pitch the same [32,34]. Typical results for the $C_2H_2 + 2.5O_2 + 70\%Ar$ mixture with roughness parameters $\sigma = 0.06$ and $\varphi = 0.13$ are shown in Fig. 3. The velocity was normalized by the theoretical CJ velocity. CJ velocities were calculated using the NASA CEA program [35].

Fig. 3a first shows the variation of the detonation velocity along the tube for $C_2H_2 + 2.5O_2 + 70\%Ar$ at an initial pressure $P_0 = 8$ kPa. Since, a number of repeated experiments at the same condition were carried out, the average value for the repeated experiments with error bars (representing the min and max values) is displayed to indicate typical "shot-to-shot" variation. In the smooth section, the detonation velocity is found to be quite constant at about 1610 m/s (~92%V_{CJ}) prior to entering the

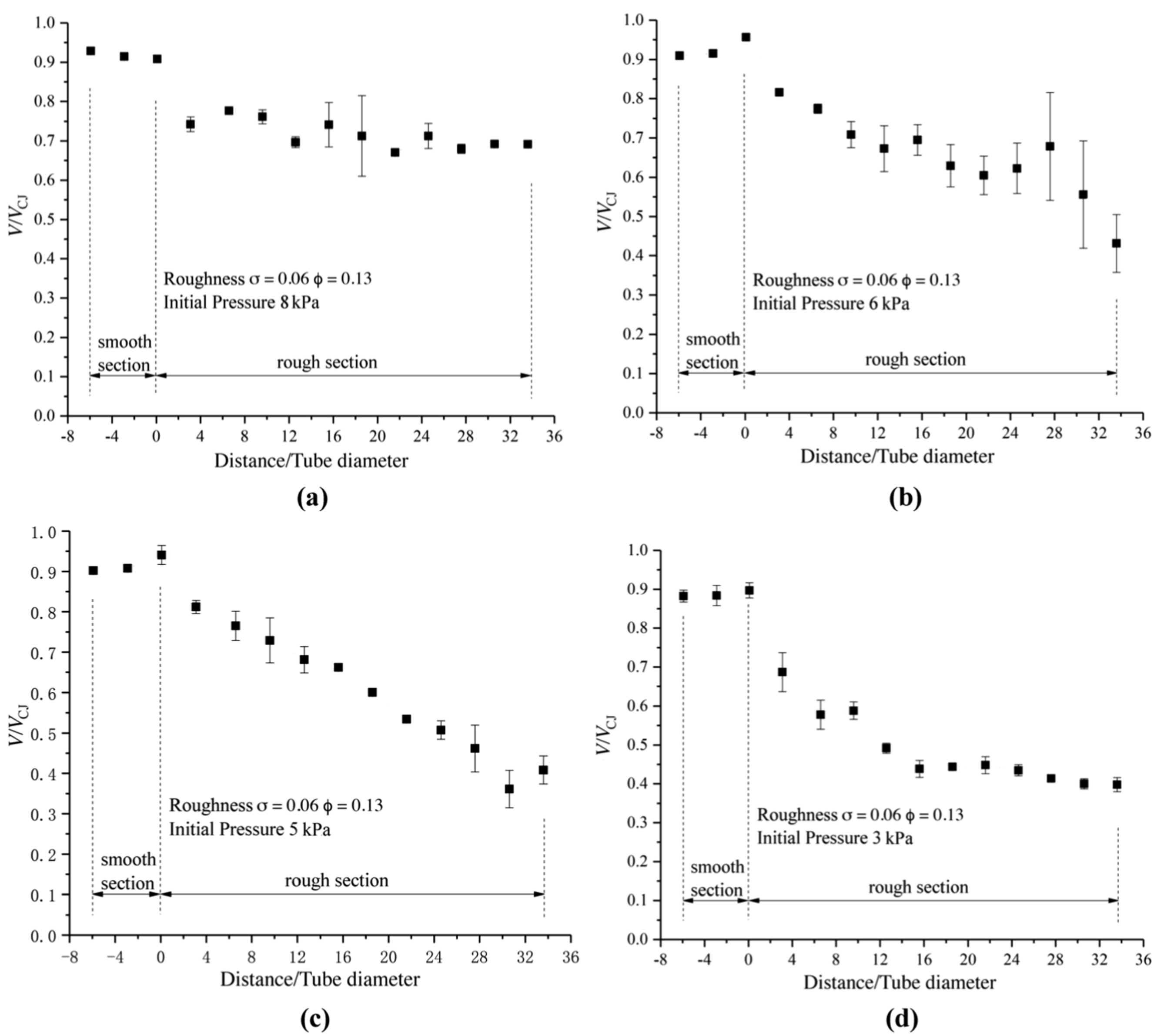

Fig. 3. Local velocity variation along the test section for $C_2H_2 + 2.5O_2 + 70\%Ar$ with roughness parameters $\sigma = 0.06$ and $\varphi = 0.13$ at a) $P_0 = 8$ kPa; b) $P_0 = 6$ kPa; c) $P_0 = 5$ kPa; and d) $P_0 = 3$ kPa. The corresponding V_{CJ} are $V_{CJ} = 1733.1$ m/s, 1722.4 m/s, 1715.7 m/s and 1697.1 m/s, respectively.

rough section. Upon entering the rough section, the detonation velocity decreases to about 1155 m/s (~66%V_{CJ}) within a distance of about four tube diameters. Subsequently, the velocity fluctuates about a mean value for the remaining 1.5 m (or about 30 tube diameters length) of the rough section.

When the initial pressure is reduced to $P_0 = 6$ kPa, the local velocity variation is shown in Fig. 3b. In the smooth section prior to entering the rough section, the mean detonation velocity was about 1560 m/s corresponding to about 90%V_{CJ}. The velocity decreased continuously for almost the entire length of the rough section of 1.9 m. Near the end of the rough section, large fluctuations of the velocity could be observed, which means the detonation velocity did not attain a steady state value after propagating in the rough section for 34 tube diameters. A longer rough section is required in the future work to observe the evolution of this unsteady propagation mode.

For a lower initial pressure $P_0 = 5$ kPa, the initial detonation velocity is about $0.9V_{CJ}$ in the smooth section. Upon entering the rough section, the detonation decayed to a velocity of about 40%V_{CJ} near the end of the tube (Fig. 3c). For an even lower initial pressure of $P_0 = 3$ kPa (Fig. 3d), the initial detonation velocity is $0.88V_{CJ}$ in the smooth section and decays in the rough section to a steady value of 40%V_{CJ} in a shorter distance of about 70 cm (about 14 tube diameters).

The results shown in Fig. 3 indicate that detonation velocity in general decreased to a lower velocity with decreasing initial pressure. Also, the propagation distance before reaching a steady value decreased for decreasing initial pressures. For low initial pressures, the detonation decreased to a value of about 40%V_{CJ}. Smoked foil records indicate that at the low velocity of about 40%V_{CJ}, the detonation had no cellular structure. We define deflagration as a combustion wave devoid of cellular structure irrespective of its velocity. Thus, we conclude that the detonation has failed and becomes a deflagration. Even though the deflagration has a relatively high velocity of about 40%V_{CJ}, no cellular structure is observed. The high velocity of the deflagration is due to the turbulence and pressure waves generated by the rough wall, which maintains a high reaction rate to permit the deflagration wave to propagate at supersonic speeds. This point of view could be verified by previous study of Teodorczyk et al. [36]. Previous studies of detonations propagation in rough (or obstacle filled) tubes refer to the high-speed combustion waves as quasi-detonation, choked flames, etc. In the present study we define a combustion wave to be a deflagration when it failed to generate instability and does not have a cellular structure.

Results of the local velocity variation along the rough section with roughness parameter and initial pressure for the $C_2H_2 + 2.5O_2 + 70\%Ar$ is shown in Fig. 4. In general, the velocity decreased with decreasing initial pressure and at some critical pressure the velocity showed an abrupt decrease to a low velocity of the order of 40%V_{CJ}. The velocity prior to the abrupt jump depends on the roughness parameter, σ. For larger degree of roughness, the detonation velocity prior to the jump is lower and hence the magnitude of the velocity jump itself is smaller. For example, for a small roughness parameter $\sigma = 0.03$, the velocity prior to the jump is about 65%V_{CJ}. Whereas for a larger roughness $\sigma = 0.13$, the velocity prior to the jump is only about 50%V_{CJ}. After the jump, the detonation velocity for all cases is about the same at about 40%V_{CJ}. We define the critical pressure when the abrupt decrease in the detonation velocity occurs as the onset of the detonation limit. The rationale for defining the detonation limits by this critical pressure is that subsequent to the abrupt jump, smoked foil records indicate that the wave has no cellular structures and thus, corresponds to a deflagration wave. In Fig. 4, we also note that the critical pressure increases with increasing roughness. Therefore, we conclude that wall roughness tends to narrow the detonation limit in contrast to the previous study of Starr et al. [32]. In the previous study by Starr et al., they considered the low velocity regime of about 40%V_{CJ} to be still a detonation rather than a deflagration. This is due to the fact they did not obtain smoked foil records of the combustion wave for the low velocity regime of ~ 40%V_{CJ} to find the absence of cellular structure.

For unstable detonations in $C_2H_2 + 5N_2O$ where the cellular pattern is irregular, the variation of detonation velocity with distance along the tube for a value of the roughness parameters of $\sigma = 0.06$ and $\varphi = 0.13$ is shown in Fig. 5. In the smooth section prior to the rough section, the detonation velocity for $P_0 = 4$ kPa is about 95%V_{CJ} (~2010 m/s), typical of detonation velocities in smooth tube of the same diameter and same initial pressure. Upon entering the rough section, the detonation velocity decreases to a steady state value of about 1500 m/s (72%V_{CJ}). For lower initial pressures of $P_0 = 3$ or 2 kPa, the velocity decreases to about $0.5V_{CJ}$ (~1060 m/s). For the unstable $C_2H_2 + 5N_2O$ mixture, Fig. 5 shows that the fluctuations of the local velocity are less than that for a stable mixture of $C_2H_2 + 2.5O_2 + 70\%Ar$. Smoked foil records also indicate the absence of cells for the low velocity regime of < 50%V_{CJ}. Thus, the wave corresponds to a deflagration wave.

Fig. 6 shows the variation of steady combustion wave velocity for different wall roughness for $C_2H_2 + 5N_2O$. Critical pressures are defined when the combustion wave velocity shows an abrupt decrease to a lower value. Detonation limits are defined when the abrupt decrease to a lower velocity occurs. In contrast to the previous results for the "stable" mixture, the velocity subsequent to the jump shows a stronger

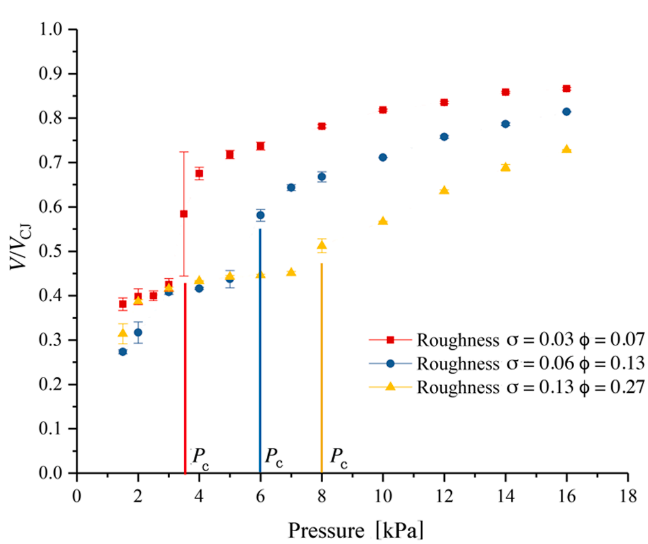

Fig. 4. Normalized velocity versus initial pressure with different wall roughness parameters for $C_2H_2 + 2.5O_2 + 70\%Ar$.

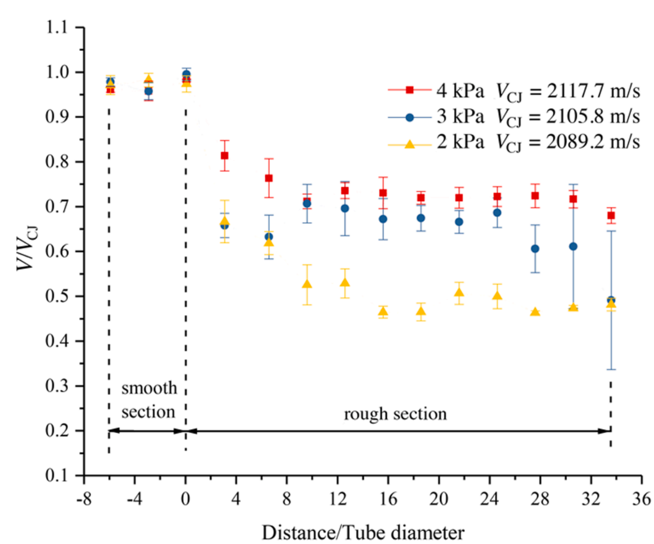

Fig. 5. Local velocity variation along the test section for $C_2H_2 + 5N_2O$ with roughness parameters σ = 0.06, φ = 0.13 at different initial pressures.

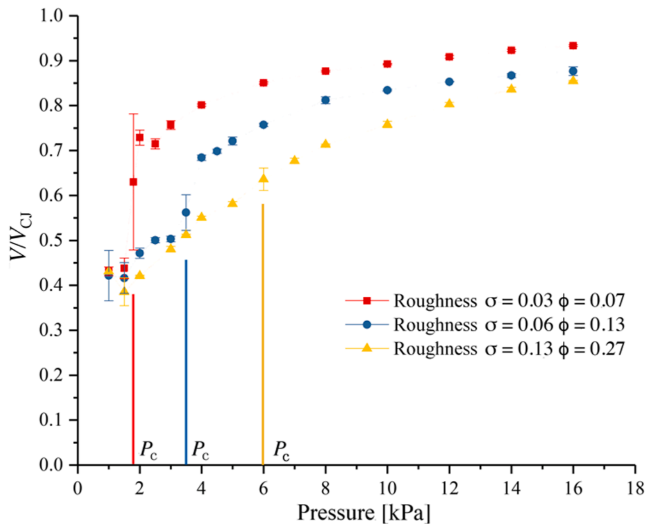

Fig. 6. Normalized velocity versus initial pressure with different wall roughness parameters for $C_2H_2 + 5N_2O$.

dependence on the initial pressure.

To observe the cellular structure of the detonation, smoked foils are inserted into the tube at the end of the rough section. Experiments indicate that it takes a distance of at least a few tube diameters before the structure recovers to that of a detonation in the smooth tube. Thus, examining the smoked foil at the beginning of the foil will provide an indication of the detonation structure in the rough section. Fig. 7 shows a series of smoked foils upstream and downstream of the rough section.

The upstream smoked foil A is in the smooth section just prior to the rough section and smoked foil B is just downstream of the rough section (Fig. 2). The length of the rough section shown in Fig. 2 is $L_r/D_t = 24$. The mixture is $C_2H_2 + 2.5O_2 + 70\%Ar$. From the velocity variation with distance (Fig. 3), we note that the detonation has reached steady state in $L_r/D_t = 24$ for 8 kPa. Fig. 7a shows that at $P_0 = 8$ kPa, the detonation structure has a lower unstable mode with a large cell size in the rough section but the detonation then recovers its initial multi headed structure after a distance of about five tube diameters. In Fig. 7b where the initial pressure is lower at $P_0 = 6$ kPa, the structure in the rough section still shows a lower unstable mode (double headed detonation) and recovering to its initial multi-headed structure regime occurs at a distance greater than eight tube diameters. The structures shown in the smoked foil B indicate that an initially multiheaded wave would degenerate to lower unstable modes in the rough section. For a still lower pressure of $P_0 = 5$ kPa, cell structure is not observed in the downstream foil B, indicating that the detonation in the rough section has failed and becomes a deflagration. As shown in Fig. 3c, we note that the detonation has decayed to $\sim 40\%V_{CJ}$ near the end of the rough section. Thus at $\sim 40\%V_{CJ}$, the detonation is devoid of cells and based on this, we conclude that for the low velocity of about $40\%V_{CJ}$, the wave is a deflagration.

Similar results are observed for the unstable mixture of $C_2H_2 + 5N_2O$ as shown in Fig. 8. From the velocity shown in Fig. 5, we note that the detonation decayed to steady state after a distance of about 16 tube diameters. In Fig. 8a, compared to the initial multi-headed structure in the foil A, the cell size in the foil B becomes much bigger and the structure shows a lower unstable mode. In Fig. 8b at $P_0 = 4$ kPa, the structure in the rough section is observed to correspond to a double-headed detonation. In Fig. 8c where $P_0 = 2$ kPa, no cell structure is observed in the downstream foil B. The velocity of the wave in the rough section at $P_0 = 2$ kPa as shown in Fig. 5 is about $50\%V_{CJ}$. Thus, at the low velocity of about 40–$50\%V_{CJ}$, combustion waves in the rough tube corresponds to a deflagration wave since cellular structure was not observed.

The results from these smoked foil experiments indicate that an initial multi-headed detonation in the smooth tube becomes a detonation of a lower unstable mode (e.g., spinning detonation) in the rough tube. Eventually, the detonation limit is encountered when no cells are obtained in the rough section (i.e., deflagration).

4. Conclusions

Detonation in rough walled tubes is studied in the present investigation in contrast to the majority of previous studies where wall roughness is obtained via periodically spaced orifice plates. The wire diameter "δ" used in the present study is small compared to the tube diameter "D_t" (i.e., $\delta/D_t \ll 1$). The present results indicate an increase in the velocity deficit due to wall roughness and a change in the detonation structure from a multi headed detonation to lower unstable modes (e.g., single headed spinning detonation) in the rough section. It is found that when the detonation velocity has decreased to less than about $50\%V_{CJ}$ (or lower), the detonation no longer has a cellular structure signifying failure. It is observed that the resulted deflagration absent of any cellular traces has still a relatively high velocity of about $40\%V_{CJ}$. Because the gasdynamic relaxation time is much shorter than the auto ignition delay time, the shock head will be cooled by expansion waves during its induction period and hence, autoignition is not likely to occur to sustain

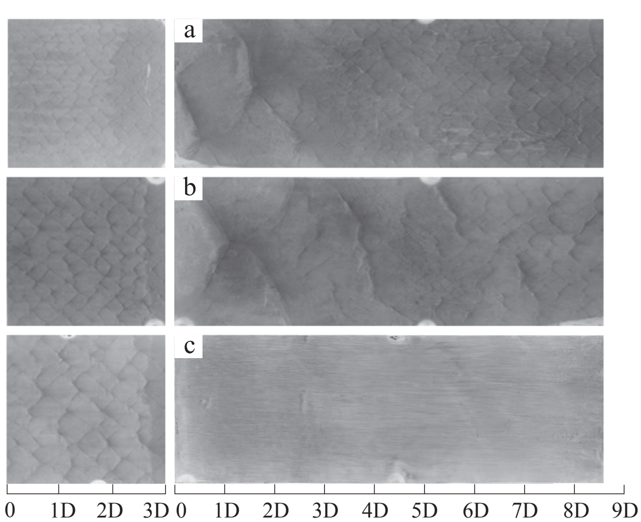

Fig. 7. Smoked foils for $C_2H_2 + 2.5O_2 + 70\%Ar$ at different initial pressures (a. $P_0 = 8$ kPa, b. $P_0 = 6$ kPa, c. $P_0 = 5$ kPa).

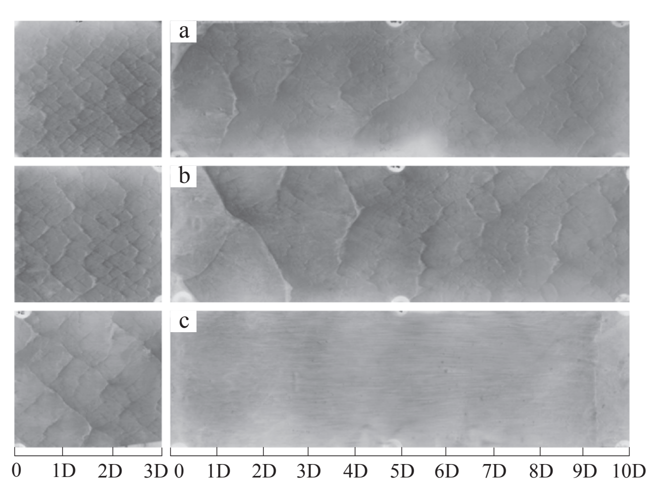

Fig. 8. Smoked foils for $C_2H_2 + N_2O$ at different initial pressures (a. $P_0 = 4$ kPa, b. $P_0 = 3$ kPa, c. $P_0 = 2$ kPa).

the detonation. The high velocity of the deflagration is due to the turbulence and pressure waves generated by the rough wall, which maintains a high reaction rate to permit the deflagration wave to propagate at supersonic speeds.

In short, detonation limit is defined based on the absence of cells in the combustion wave irrespective of the wave velocity. Based on the structure of the wave to define the limits is more appropriate. The velocity-based terminology used in the literature such as choked flame, quasi-detonation, high speed deflagration, etc., to describe high speed supersonic combustion waves can be avoided.

The present study also found that the detonation limit is narrower due to wall roughness in contrast to the previous conclusion of Starr et al. [32]. In the previous study of Starr et al., the low velocity waves of $V \sim 40\% V_{CJ}$ was still considered as detonation. This is due to the fact that cell structure was not determined in the previous study by Starr et al. The effect of wall roughness on the detonation structure reducing it to a lower unstable mode is in accord with the previous streak schlieren observations of Brochet [37] who also used wire springs to generate wall roughness.

CRediT authorship contribution statement

Yuanyi Liu: Investigation, Validation, Methodology. **John H.S. Lee:** Investigation, Formal analysis, Supervision, Writing - original draft. **Houzhang Tan:** Investigation, Supervision. **Hoi Dick Ng:** Investigation, Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and China Scholarships Council No. 201506280086.

References

[1] Lee JHS. The Detonation Phenomenon. Cambridge University Press, Cambridge; 2008. https://doi.org/10.1017/CBO9780511754708.
[2] Camargo A, Ng HD, Chao J, Lee JHS. Propagation of near-limit gaseous detonations in small diameter tubes. Shock Waves 2010;20(6):499–508. https://doi.org/10.1007/s00193-010-0253-3.
[3] Lee JHS, Jesuthasan A, Ng HD. Near limit behavior of the detonation velocity. Proc Combust Inst 2013;34(2):1957–63. https://doi.org/10.1016/j.proci.2012.05.036.
[4] Gao Y, Ng HD, Lee JHS. Minimum tube diameters for steady propagation of gaseous detonations. Shock Waves 2014;24(4):447–54. https://doi.org/10.1007/s00193-014-0505-8.
[5] Zhang B, Pang L, Gao Y. Detonation limits in binary fuel blends of methane/hydrogen mixtures. Fuel 2016;168:27–33. https://doi.org/10.1016/j.fuel.2015.11.073.
[6] Zhang B, Liu H, Yan B. Investigation on the detonation propagation limit criterion for methane-oxygen mixtures in tubes with different scales. Fuel 2019;239:617–22. https://doi.org/10.1016/j.fuel.2018.11.062.
[7] Zhang B, Liu H, Li Y. The effect of instability of detonation on the propagation modes near the limits in typical combustible mixtures. Fuel 2019;253:305–10. https://doi.org/10.1016/j.fuel.2019.05.006.
[8] Zhang B, Liu H, Yan B, Ng HD. Experimental study of detonation limits in methane-oxygen mixtures: Determining tube scale and initial pressure effects. Fuel 2020;259:116220. https://doi.org/10.1016/j.fuel.2019.116220.
[9] Wang LQ, Ma HH, Shen ZW, Yue B, Cheng YF, Fan ZQ. Experimental investigation of methane-oxygen detonation propagation in tubes. Appl Thermal Eng 2017;123:1300–7. https://doi.org/10.1016/j.applthermaleng.2017.05.045.
[10] Gao Y, Lee JHS, Ng HD. Velocity fluctuation near the detonation limits. Combust Flame 2014;161(11):2982–90. https://doi.org/10.1016/j.combustflame.2014.04.020.
[11] Jackson S, Lee BJ, Shepherd JE. Detonation mode and frequency analysis under high loss conditions for stoichiometric propane-oxygen. Combust Flame 2016;167:24–38. https://doi.org/10.1016/j.combustflame.2016.02.030.
[12] Zhang B, Wang C, Shen X, Yan L, Yan B, Xia Y. Velocity fluctuation analysis near detonation propagation limits for stoichiometric methane–hydrogen–oxygen mixture. Int J Hydrogen Energy 2016;41:17750–9. https://doi.org/10.1016/j.ijhydene.2016.08.017.
[13] Cao W, Gao D, Ng HD, Lee JHS. Experimental investigation of near-limit gaseous detonations in small diameter spiral tubing. Proc Combust Inst 2019;37(3):3555–63. https://doi.org/10.1016/j.proci.2018.08.027.
[14] Cross M, Ciccarelli G. DDT and detonation propagation limits in an obstacle filled tube. J Loss Prev Process Ind 2015;36:382–8. https://doi.org/10.1016/j.jlp.2014.11.020.
[15] Ciccarelli G, Cross M. On the propagation mechanism of a detonation wave in a round tube with orifice plates. Shock Waves 2016;26(5):587–97. https://doi.org/10.1007/s00193-016-0676-6.
[16] Ciccarelli G, Wang Z, Lu J, Cross M. Effect of orifice plate spacing on detonation propagation. J Loss Prev Process Ind 2017;49:739–44. https://doi.org/10.1016/j.jlp.2017.03.014.
[17] Manzhalei VI. Gas detonation in a channel with transverse ribs. Combust Expl Shock Waves 2007;43:567–71. https://doi.org/10.1007/s10573-007-0075-5.
[18] Gamezo VN, Ogawa T, Oran ES. Flame acceleration and DDT in channels with obstacles: Effect of obstacle spacing. Combust Flame 2008;155:302–15. https://doi.org/10.1016/j.combustflame.2008.06.004.
[19] Zhang B, Hong L. The effects of large scale perturbation-generating obstacles on the propagation of detonation filled with methane-oxygen mixture. Combust Flame 2017;182:279–87. https://doi.org/10.1016/j.combustflame.2017.04.025.
[20] Wang LQ, Ma HH, Shen ZW, Lin MJ, Li XJ. Experimental study of detonation propagation in a square tube filled with orifice plates. Int J Hydrogen Energy 2018;43(9):4645–56. https://doi.org/10.1016/j.ijhydene.2018.01.080.
[21] Wang LQ, Ma HH, Shen ZW. Effect of orifice plates on detonation propagation in stoichiometric hydrogen-oxygen mixture. Exp Therm Fluid Sci 2018;99:367–73. https://doi.org/10.1016/j.expthermflusci.2018.08.012.
[22] Sun XX, Lu S. Effect of orifice plate on the transmission mechanism of a detonation wave in hydrogen-oxygen mixtures. Int J Hydrogen Energy 2020;45(22):12593–603. https://doi.org/10.1016/j.ijhydene.2020.02.162.
[23] Laffitte P. Sur la formation de l'onde explosive. C R Acad Sci 1923;176:1392–4.
[24] Shchelkin KI. Detonation of gases in rough tubes. Zh. Teknich. Fiz. SSSR. 1947;17:613–8.
[25] Chapman WR, Wheeler RV. The propagation of flame in mixtures of methane and air. Part IV. The effect of restrictions in the path of the flame. J Chem Soc 1926:2139–47. https://doi.org/10.1039/jr9262902139.
[26] Babkin V, Kozachenko L. The onset of detonation in a gas in tubes with rough walls. Prikl. Mat. Tekh. Fiz. 1960;3:165–74.
[27] Ciccarelli G, Dorofeev S. Flame acceleration and transition to detonation in ducts. Prog Energy Combust Sci 2008;34:499–550. https://doi.org/10.1016/j.pecs.2007.11.002.
[28] Dorofeev SB. Flame acceleration and explosion safety applications. Proc Combust Inst 2011;33:2161–75. https://doi.org/10.1016/j.proci.2010.09.008.
[29] Guénoche H. The detonation and deflagration of gas mixtures. Rev Inst Français Pétrole 1949;4:48–69.
[30] Manson N, Brochet C, Brossard J, Pujol Y. Vibratory phenomena and instability of self-sustained detonations in gases. Proc Combust Inst 1963;9:461–9. https://doi.org/10.1016/S0082-0784(63)80055-7.
[31] Zhang B. The influence of wall roughness on detonation limits in hydrogen–oxygen mixture. Combust Flame 2016;169:333–9. https://doi.org/10.1016/j.combustflame.2016.05.003.
[32] Starr A, Lee JHS, Ng HD. Detonation limits in rough walled tubes. Proc Combust Inst 2015;35(2):1989–96. https://doi.org/10.1016/j.proci.2014.06.130.
[33] Zhang B, Liu H, Wang C. On the detonation propagation behavior in hydrogen-oxygen mixture under the effect of spiral obstacles. Int J Hydrogen Energy 2017;42(33):21392–402. https://doi.org/10.1016/j.ijhydene.2017.06.201.
[34] Li J, Yang T, Wang X, Ning J. Propagation Mechanism of Detonations in Rough-Walled Tube. In: Int. Symp. on Shock Waves, pp. 253-260. Springer; 2017. https://doi.org/10.1007/978-3-319-91020-8_28.
[35] Gordon S, McBride BJ. Computer Program for Calculations of Complex Chemical Equilibrium Compositions and Applications. NASA Tech Rep RP-1311-P21996; 1994.
[36] Teodorczyk A, Lee JHS, Knystautas R. Photographic study of the structure and propagation mechanisms of quasi-detonations in rough tubes. AIAA Prog Astronaut Aeronaut 1991;133:223–40. https://doi.org/10.2514/5.9781600866067.0223.0240.
[37] Brochet C. Contribution à l'Etude des Détonations Instable dans les Mélanges Gazeux. PhD thesis. France: University of Poitiers; 1966.