Velocity Deficits in Thin Channels for a Cylindrically Expanding Detonation

Hoi Dick Ng†
Concordia University
Department of Mechanical and Industrial Engineering, Montréal, Québec, H3G 1M8, Canada

Jiajun Wang and John H.S. Lee
McGill University
Department of Mechanical Engineering, Montréal, Québec, H3A 2K6, Canada

1 Introduction

Unlike detonations in constant area ducts, the surface area of a cylindrical (or spherical) detonation increases with radius. The latter will influence the stability of the wave as new transverse waves must be generated to keep the average spacing (cell size) the same [1]. The curvature of the detonation front can also affect the structure and hence, the propagtion velocity. However, cylindrical (and spherical) detonations are almost always directly initiated since DDT is highly improbable for diverging detonations. Thus the detonation is initially highly overdriven and, once decayed to the CJ condition, the radius is usually large as compared to the characteristic thickness (e.g. cell length) of the wave. The curvature of the wave becomes small at relatively larger radius. Nevertheless, the surface area of the wave still increases with radius (e.g., the circumference for cylindrical geometry), hence requiring the continuous geneneration of new transverse waves. The dynamics of cylindrical detonations may thus still differ from that of a planar detonation in a constant area rectangular channel even at larger radii.

Only few studies exist in the literature on the velocity of cylindrical detonations which are based on relatively thick cylindrical channel compared to the cell size, e.g., [2, 3]. In the present study, thin cylindrical chambers are used and wave velocities are measured with decreasing mixture sensitivity (i.e., reducing pressure) until failure to obtain the limits for cylindrical detonation to compare with constant area channel (or annular channel). The objective of this work is to study the velocity deficit behavior and distinguish the failure mechanism of the cylindrical detonation in a thin channel, i.e., the dominant effect between the thin channel width or the role of new transverse wave generation along the increasing circumference during divergence. Since the role of transverse wave generation is of interest for steady self-sustained propagation of cylindrical detonation, two unstable mixtures typical of irregular cellular detonation pattern are used.

2 Experimental details

The experimental apparatus consists of a 1-m long, 2.54-cm diameter circular steel tube connected at the center with two 61-cm diameter circular parallel plates with 2.54-cm thickness. A Delrin spacing ring with 53-cm inner diameter and 61-cm outer diameter is clamped in the middle creating the thin channel between the two parallel plates. Three different channel widths *w* are considered: 1.5, 3.2 and

†Correspondence to: hoing@encs.concordia.ca

6.4 mm. A detonation wave is first initiated via a high-voltage capacitor discharge and propagates in the circular tube. It then emerges and diverges from the center of the flat channel. The time-of-arrival of the combustion wave in the channel test section was measured by optical probes located along two different radii of the channel between the two parallel plates. The first probe is located at a radius of 38 mm which is of the order of 800 reaction zone length of the detonation and hence, the curvature due to the divergence can be considered negligible. Subsequent probes are located roughly 39 mm apart. These diagnostic permitted the trajectory of the wave front, and hence the velocity, to be determined. A sketch of the experimental apparatus is shown in Fig. 1. Two unstable mixtures, i.e., stoichiometric acetylene-oxygen and acetylene-nitrous oxide mixtures, were used. The sensitivity of each tested mixture was varied by the initial pressure to approach the detonation limit. Each explosive mixture is prepared in a separate mixing tank via the partial pressure method and allowed to mix for at least 24 hours prior to being used. The CJ detonation velocity V_{CJ} of various mixture conditions is calculated using the NASA CEA program [4].

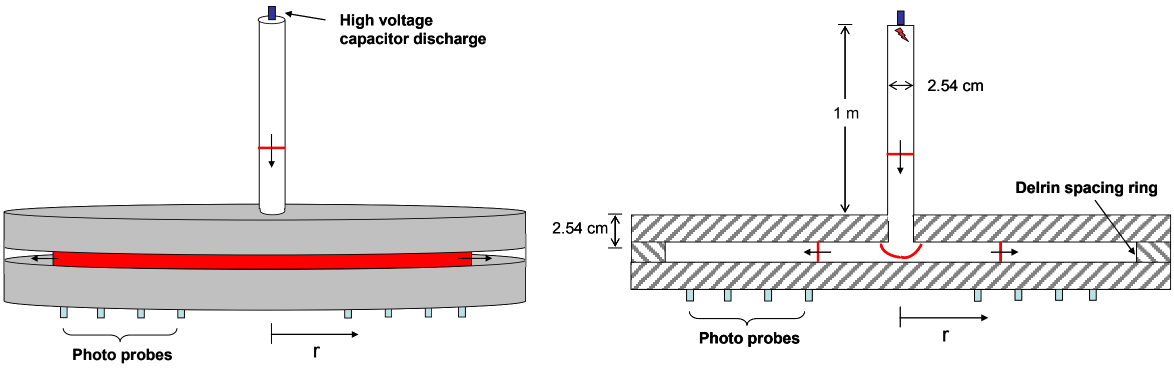

Figure 1. A schematic of the experimental apparatus with the cut-out view

3 Results and discussions

For a given mixture and channel width, the detonation limits are approached by progressively decreasing the initial pressure p_o. Figure 2 first shows the variation of the detonation velocity with initial pressure in the acetylene-oxygen mixture for the three channel widths. It is worth noting that in the figure only global averaged values of the local wave velocities are plotted when the detonation still propagates at an approximately steady velocity with small local fluctuations. In other words, the spectrum of unstable phenomena typically observed near the limits [5-7] is not considered in these results. The results first show the importance of the channel width. For a given initial pressure, the velocity deficit increases with smaller channel width. For example, at an initial pressure of p_o = 10 kPa, the velocity deficit for both 3.2 and 6.4-mm channel width remains within 5%. In other word, at that pressure, the rate of new transverse waves generation is sufficient to compensate the increase in circumference for the steady, self-sustained detonation propagation. However, by reducing the channel width to 1.5 mm, the velocity deficit increases to approximately 13%. Thus, this indicates that the thickness effect of the channel dominates the detonation dynamics and causes the velocity deficit leading to failure. In addition, the present results exhibit similar behaviors as those typically obtained for detonations in constant area circular tubes [8, 9], narrow gaps [10] and annular channels [11, 12]. For instance, well within the propagation limits the detonation velocity remains close to the CJ values. As the limit is approached by further decreasing the initial pressure, the velocity progressively deviates from CJ values until the limit of detonation is reached, as evidenced in the figure by a sudden increase in velocity deficit. The velocity is also observed to be in the range of $0.8V_{CJ} \le V \le V_{CJ}$ and comparable in all three channel widths.

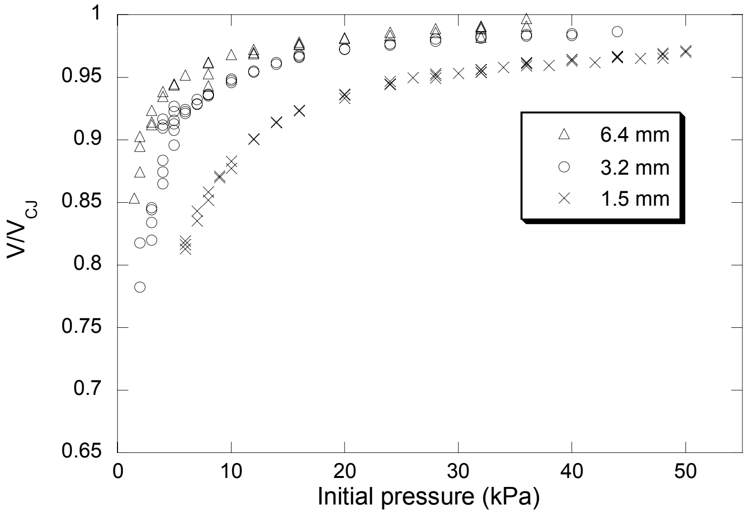

Figure 2. Detonation velocity (normalized with its theoretical CJ velocity value) as a function of the initial pressure, for the $C_2H_2 + 2.5O_2$ mixture in three different channel widths.

The detonation cell size of a stoichiometric acetylene-oxygen mixture as a function of initial pressure is readily available in the literature and can be collected from the GALCIT detonation database [13]. Whereas the cell size λ is the length scale that characterizes the sensitivity of the explosive mixture, the channel width w represents the physical length scale of the boundary condition that determines the detonation limit (for a given mixture at a given initial pressure). Thus, the ratio w/λ represents an appropriate dimensionless parameter defining the detonation limit. Figure 3 shows alternatively the velocity deficit obtained from the present experiments for the acetylene-oxygen mixture in three different channel widths as a function of w/λ. By using the scaling ,w/λ, all the results appear to collapse into a single curve. As shown in the figure, the velocity deficit also increases sharply near a critical value of w/λ, thus defining the limits. The limiting value of w/λ for these present experimental data is found to be approximately $w/\lambda \sim 1.0$. Notably, this is different from the single headed spin criterion $1/\pi$ commonly considered as the limit criterion for circular tubes. The $w/\lambda \sim 1.0$ is perhaps due to the fact that a single-headed spinning detonation cannot be formed in two-dimensional thin channels and that an unstable detonation requires at least one cell in the channel width to maintain its self-propagation.

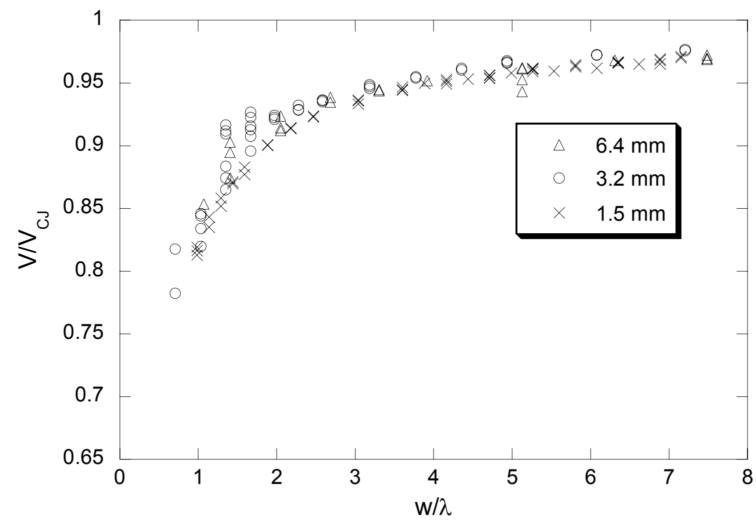

Figure 3. Detonation velocity (normalized with its theoretical CJ velocity value) as a function of w/λ, for the $C_2H_2 + 2.5O_2$ mixture in three different channel widths.

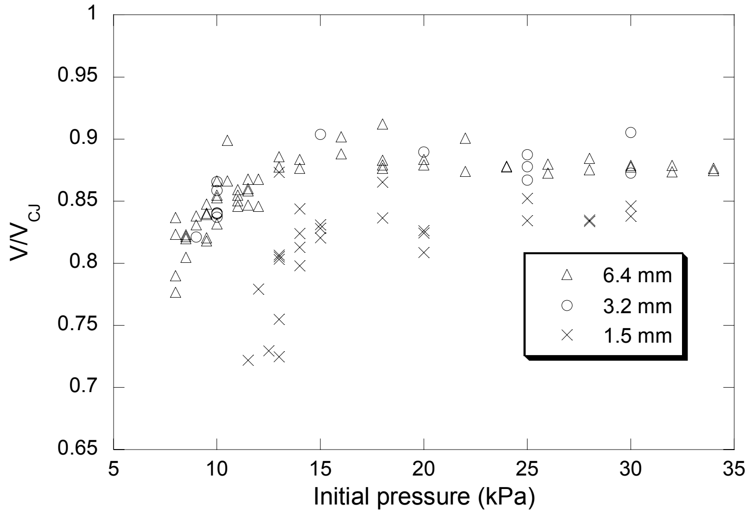

Figure 4. Detonation velocity (normalized with its theoretical CJ velocity value) as a function of the initial pressure, for the C_2H_2 + $5N_2O$ mixture in three different channel widths.

Figure 4 shows the same type of velocity measurement for the other unstable mixture of stoichiometric acetylene-nitrous oxide in three different channel widths. Overall, similar trend is observed as in the stoichiometric acetylene-oxygen mixture. For the acetylene-nitrous oxide mixture which is more unstable, it appears that the maximum velocity deficit, for which a steady detonation can still be observed, is increased. Another observation from Fig. 4 is that the obtained data is more scattered. One of the reasons can be explained from the observation of asymmetrical divergence of the propagating detonation wave and hence, causing deviation of the velocity results measured along fixed radial distances from shot-to-shot even at the same initial condition. More experiments are currently being carried out to refine these results.

4 Concluding remarks

In this investigation we study the propagation of the diverging detonation in thin cylindrical channels using two unstable mixtures of stoichiometric acetylene-oxygen and acetylene-nitrous oxide. The velocity deficit behavior, as the limit is approached by decreasing the initial pressure, is reported. For a diverging detonation, the necessity of transverse wave generation as the surface area along the circumference increases is crucial in maintaining the steady, self-sustained propagation. If transverse waves are not generated, the cylindrical detonation fails as it expands. However, in the present study, the effect of channel width is found to be the dominant mechanism for the velocity deficit leading to the limit. The observed velocity deficit exhibits a similar trend as those previously reported in circular tubes and annular channel. Using the cell sizes available for the acetylene-oxygen mixture and w/λ in the analysis, all the velocity deficit data of this mixture are collapsed into a single curve and the limiting w/λ is found to be approximately equal to 1.0. In this configuration where a single-headed spin detonation is not possible, at least one cell at the detonation front is necessary for the steady propagation of the detonation.

Acknowledgment

This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

[1] Lee JHS. (2008) The Detonation Phenomenon. Cambridge University Press.

[2] Lee JHS et al. (1965) Two-dimensional unconfined gaseous detonation waves. Proc. Combust. Inst. 10: 805-815.

[3] Aminallah M et al. (1993) Cylindrical detonations in methane-oxygen-nitrogen mixtures. Prog. Astronaut. Aeronaut. 153: 203-228.

[4] McBride BJ, Gordon S. (1996) Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. RP-1311, NASA Reference Publication, Cleveland.

[5] Lee JJ et al. (1995) Doppler interferometry study of unstable detonations. Shock Waves 5:175-181.

[6] Jackson S et al. (2009) Experimental detonation propagation under high loss conditions. Proc. 22nd ICDERS, Minsk, Belarus July 27-31, 2009.

[7] Gao Y et al. (2014) Velocity fluctuations near the detonation limits. Combust. Flame 161(11): 2982-2990.

[8] Camargo A et al. (2010) Propagation of near-limit gaseous detonations in small diameter tubes. Shock Waves 20(6): 499-508.

[9] Gao Y et al. (2014) Minimum tube diameters for steady propagation of gaseous detonations. Shock Waves 24(4): 447-454.

[10] Ishii K, Monwar M. (2011) Detonation propagation with velocity deficits in narrow channels. Proc. Combust. Inst. 33: 2359–2366.

[11] Chao J et al. (2009) Detonability limits in thin annular channels. Proc. Combust. Inst. 32: 2349-2354.

[12] Lee JHS et al. (2013) Near limit behavior of the detonation velocity. Proc. Combust. Inst. 34: 1957-1963.

[13] Kaneshige M, Shepherd JE. (1997) Detonation database. GALCIT Technical Report FM97. Web page at http://www.galcit.caltech.edu/detn_db/html/db.html