

Near-limit propagation of detonations in annular channels

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1 Introduction

In this study, the near-limit propagation of detonations in annular channels is investigated. Most existing research conducted on detonation limits are carried out in circular tubes [1]. Rectangular tubes have been used for velocity deficit measurements and compared with circular tubes [2], but a direct comparison of the near-limit propagation of detonations in different geometries has not been made. Near-limit studies have been conducted in narrow channels [3], but in such configurations the effect of edge walls may influence the propagation of the detonation. For this reason, Chao et al. [4] attempted to study detonability limits in annular channel. However, their study was conducted using a short annular test section of only 360 mm in length. A long length of propagation is necessary in near limit studies since the detonation becomes unstable and is needed to be observed over a long length of travel. Therefore, the present study investigates the near-limit propagations of detonation in a much longer annular channels test section. The experimental results will also be compared to round tubes to elucidate the effect of geometry on the near limit propagation of detonations. The limit will be approached by reducing the initial pressure of the explosive mixture.

Two types of mixtures are investigated in the present work: mixtures highly diluted with argon and undiluted methane-oxygen and acetylene-nitrous oxide diluted with 50% argon. High argon diluted mixtures possess a piecewise laminar ZND structure while most mixtures have highly irregular and turbulent structures [5][6]. Previous studies also indicate that mixtures with high argon dilution not only exhibit different characteristic in their structure but in failure as well [7][8][9]. Therefore, it is of interest to investigate if there is any difference in the near-limit propagation of detonations in annular channel between the two types of mixtures. The detonation velocity and the dynamic structure of the detonation via smoke foil technique will be investigated.

2 Experimental details

The experimental apparatus consist of a 0.305 m long, 25.4 mm diameter steel driver section followed by a steel detonation tube totalling 4.16 m in length with a diameter of 65 mm. The annular test section is created by inserting a brass tube of 1.52 m in length supported by fins into the end of the detonation tube. Three different brass tubes are used to study three annular channel gaps: $w = 3.175$, 6.35 and 9.525 mm. The leading edge of the brass tube is chamfered to prevent any wave process from affecting the propagation of the detonation wave. A sketch of the experimental apparatus is shown in Fig. 1.

Premixed stoichiometric mixtures of methane-oxygen, acetylene-nitrous oxide diluted with 50% argon and acetylene-oxygen diluted with 70% argon were tested. The sensitivity of the mixture was varied by the initial pressure. To facilitate the initiation of a detonation, a driver mixture of equimolar acetylene-oxygen was released into the driver section seconds before ignition to avoid mixing with the explosive mixture of interest. Direct initiation of the incident CJ detonation in the upstream section was achieved via a high energy spark.

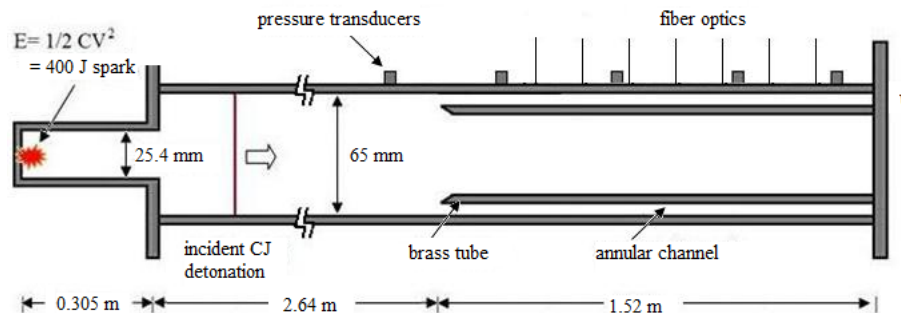


Fig. 1. Schematic of experimental apparatus.

Fiber optics and a PCB pressure transducer were used to measure the time of arrival of the incident CJ detonation in the smooth tube section. The time of arrival of the combustion wave in the annular channel test section was measured by 12 fiber optics roughly 130 mm apart as well as up to 4 pressure transducers. These diagnostics permitted the trajectory of the wave front to be determined. Smoke foil technique was also used to study the structure of the detonation wave.

3 Results and discussion

Fig. 2 shows the variation of the normalized detonation velocity in acetylene-oxygen diluted with 70% argon mixture for the three annular channels as a function of the inverse of the theoretical ZND induction length, computed using the Konnov chemical kinetic mechanism [10]. Results from 65 and 44 mm diameter round tubes are also included for comparison. The trends of the experimental results are also shown. The induction length is normalized with either the channel width or tube diameter denoted by the parameter L . Although the cell size should be taken as the true measure of the chemical sensitivity of the detonation, the cell size must be obtained experimentally and with it enters measuring uncertainty. For this reason, the ZND induction zone length will be taken as the chemical sensitivity length scale. Therefore, the parameter (L/Δ_{ZND}) represents the relative role of the geometry, manifested by wall losses, to the chemical sensitivity of the mixture. The first observation from Fig. 2 is that the results from the different annular channels all collapse onto a single curve. This indicates that within the limits of detonation, where the value of the parameter (L/Δ_{ZND}) is large, the boundary conditions play little influence of the detonation wave and therefore the velocity deficit is small. In annular channels, well within the limits of detonation, the velocity deficit is within 10% of CJ values. When (L/Δ_{ZND}) becomes small, boundary conditions start to influence the detonation wave resulting in larger velocity deficits. As the limit is approached, the measured detonation velocity deviates from the CJ values and a sharp decrease in the velocity is observed near the limit. A minimum velocity of about 70% CJ values is observed in all three channels. This demonstrates that once the temperature in the reaction zone falls below auto-ignition values, shock compression is no longer sufficient to support the detonation. In annular channels, the limiting value of (L/Δ_{ZND}) is approximately 10. The limiting value of (L/Δ_{ZND}) in round tubes is larger than annular channels because the ZND length is normalized with the tube diameter. This value is found to be about 40 to 50 in round tubes where the maximum velocity deficit is about 15% CJ values.

Fig. 3 shows the variation of the normalized detonation velocity with (L/Δ_{ZND}) in methane-oxygen mixture for the three annular channels. Again it is observed that all the results from the three annular channels can be represented by a single curve. Well within the limits of detonation, the detonation velocity deficit is about 10% of CJ values in all three cases. As the limit is approached, the detonation velocity deviates from the CJ values. In methane-oxygen mixtures, the minimum velocity observed in annular channels is about 75% in the 9.525 mm channel and is of the order of 50% CJ values for the 6.35 and 3.175 mm channel gaps. This is reminiscent of the effect of rough walls on unstable detonations which can sustain a steady propagation of a detonation with velocity deficits of the order of 50% CJ values [13]. The effect of the annular channel thus helps the detonation to propagate at lower velocities than that found in smooth round tubes, where the detonation is found to fail below a velocity of 80% CJ value. Although the average propagating velocity is low, instabilities still provide local high temperatures to effect ignition in methane-oxygen mixtures. The limiting value of (L/Δ_{ZND}) is approximately unity indicating that the failure is induced by the strong influence of the boundary when the channel width is comparable to the ZND induction length. The limiting value in round tubes is larger than annular channels. Annular channel results from acetylene-nitrous oxide diluted with 50% argon mixtures also fall onto a single curve. The limiting (L/Δ_{ZND}) value is about 5 in annular channels and 10 in round tubes with a minimum velocity of 70 and 80% CJ values, respectively.

Fig. 4 shows the variation of the normalized detonation velocity with $1/(L/\Delta_{ZND})$ in acetylene-oxygen diluted with 70% argon and methane-oxygen mixture for the three annular channels. The parameter $1/(L/\Delta_{ZND})$ characterizes the normalized curvature. The general trends of the experimental results are indicated by red solid lines. The theoretical detonation velocity using the Fay-Dabora model for the velocity deficit [1][11][12] is also shown for the 6.35 mm annular channel in both mixtures. The first observation from Fig. 4 is the difference between the two mixtures in the behavior of the detonation velocity with $1/(L/\Delta_{ZND})$. Detonations highly diluted with argon are more sensitive to the parameter than undiluted mixtures. The experimental results for detonations highly diluted with argon indicate a stronger dependence of the velocity deficit on the inverse of the normalized channel height than the theoretical model. The theoretical model predicts failure at a value of 0.18 for the 6.35 mm channel while experimental results indicate a value of 0.1. Also, the model predicts failure at a detonation velocity of about 70% CJ values where experimental results indicate a lower velocity of 65% CJ values. Experimental results from methane-oxygen mixture show a steeper slope in round tubes indicating a faster velocity deficit with the inverse of the normalized diameter than the inverse of normalized channel height. Near the limit, the velocity deficit is observed to deviate from the straight line behavior, as suggested by the red broken lines. This suggests that losses to the boundary layer may not be the failure mechanism in methane-oxygen mixtures. The theoretical model shows a stronger dependence on the $1/(L/\Delta_{ZND})$ parameter than the experimental results. Failure is predicted at a detonation velocity of 84% CJ values where detonations propagating at relatively steady velocities of the order of 50% CJ values are observed.

Smoked foil technique was also used to study the structure of the detonation wave in the channels. In round tubes, the structure of the detonation wave tends towards a single head spinning wave near the limit. Spinning detonations were repeatedly observed over a range of conditions prior to failure. Spinning detonations have also been observed in annular channels. For example, Fig. 5 shows a smoked foil record of a spinning detonation in $C_2H_2 + 5N_2O + 50\%Ar$ mixture propagating in a 6.35 mm annular channel. Therefore, even in a thin channel where the ratio of the channel height over the circumference is about 0.03, a single head spinning detonation can exist. In annular channels, the detonation structure fluctuates near the limit and so the spinning structure is not repeatedly observed prior to failure. The detonation structure for $C_2H_2 + 2.5O_2 + 70\%Ar$ and $C_2H_2 + 5N_2O + 50\%Ar$ mixtures is significantly affected by the boundary layer in the 3.175 mm annular channel and Fig. 6

shows an example of this phenomenon. Triple point trajectories, which are relatively straight in high argon diluted mixtures, are wavy in the thinnest channel.

4 Conclusion

The detonation velocity is observed to decrease rapidly as the limit is approached and the minimum velocity before failure depends on the mixture and boundary condition (i.e. channel height or tube diameter) and can be as low as 55% CJ values. When the channel height is normalized with respect to the ZND induction length, the velocity curves for different channel height are found to coalesce to form a single curve. For methane-oxygen detonations failure occurs when the channel height is of the order of the ZND induction length when the wall effect began to exert a strong influence on the detonation structure. For highly diluted mixture of $C_2H_2+2.5O_2$ with argon, the failure occurs at a larger ratio of (L/Δ_{ZND}) , indicating that the channel height began to exert an influence on the velocity through the wave curvature. The velocity is observed to vary linearly with $1/(L/\Delta_{ZND})$, but for methane-oxygen mixtures the velocity is observed to remain relatively constant at the minimum velocity for a range of values of $1/(L/\Delta_{ZND})$ before failure. Of particular interest is the observation a single headed spinning detonation (analogous to a single headed spin in circular tubes) in thin annular channels where the height over the diameter is much less than one.

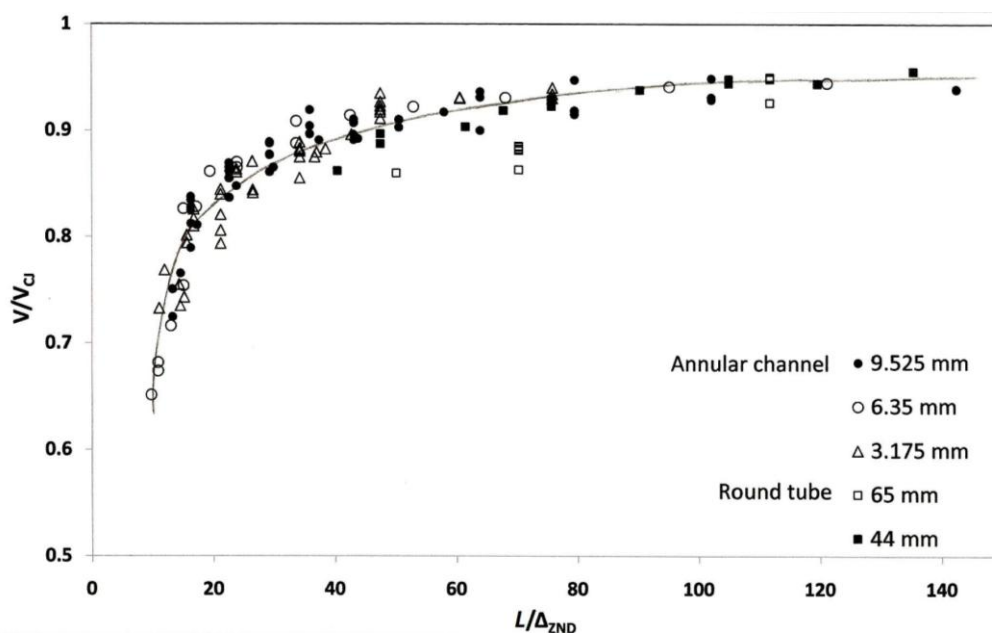


Fig. 2. Normalized detonation velocities as a function of L/Δ_{ZND} in $C_2H_2 + 2.5O_2 + 70\% Ar$ mixture for 9.525, 6.35 and 3.175 mm annular channels.

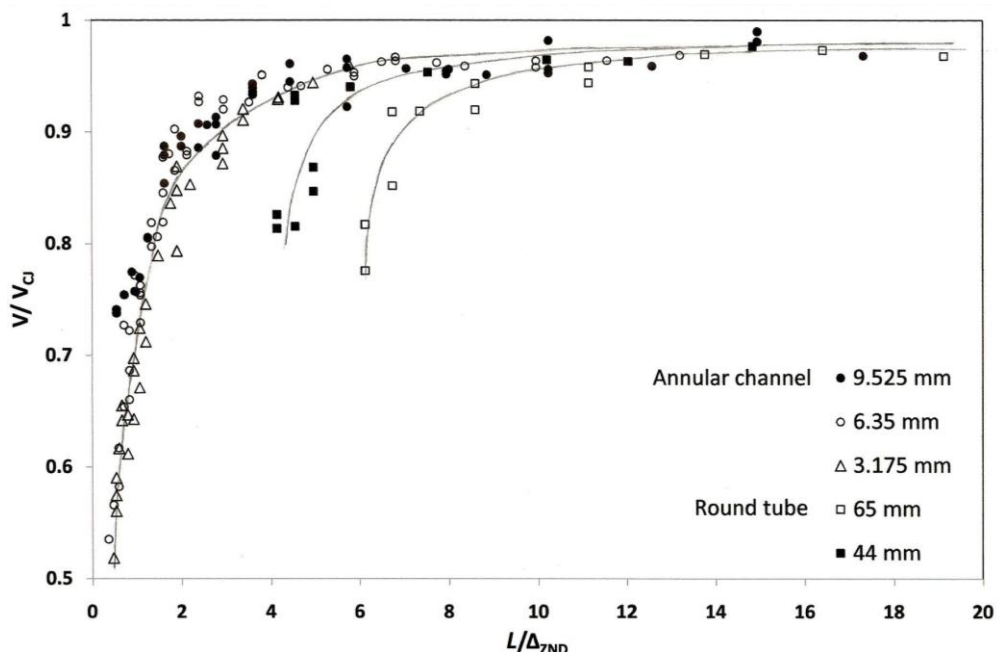


Fig. 3. Normalized detonation velocities as a function of L/Δ_{ZND} in $CH_4 + 2O_2$ mixture for 9.525, 6.35 and 3.175 mm annular channels.

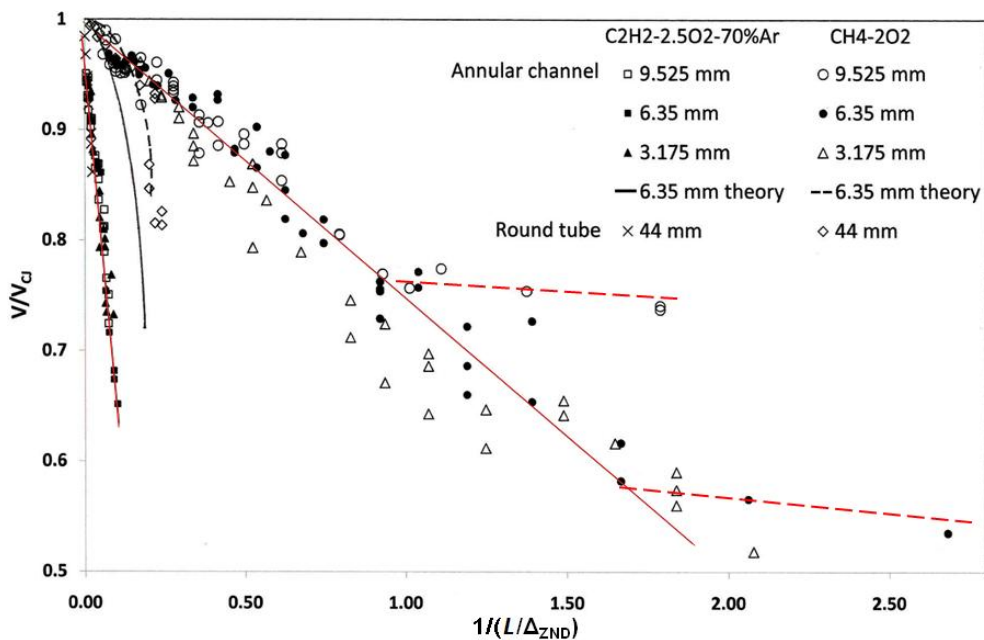


Fig. 4. Normalized detonation velocities as a function of $1/(L/\Delta_{ZND})$ in $C_2H_2 + 2.5O_2 + 70\% Ar$ and $CH_4 + 2O_2$ mixture for 9.525, 6.35 and 3.175 mm annular channels.



Fig. 5. Smoked foil records of a spinning detonation (6.35 mm annular channel, $C_2H_2 + 5N_2O + 50\%Ar$ mixture).



Fig. 6. Smoked foil records of a spinning detonation (3.175 mm annular channel, $C_2H_2 + 2.5O_2 + 70\%Ar$ mixture).

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