Detonation Diffraction from an Annular Channel

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1 Introduction

When a detonation wave propagating down a rigid round tube exits the tube into open space filled with the same reactive mixture, the detonation will fail if the tube has a diameter less than some critical value, referred to as the critical diameter, d_c. Should $d > d_c$, the detonation will re-initiate and continue to propagate once it exits its previous confinement [1]. Similar to initiation energy, this dynamic parameter can be determined much more precisely than the detonation cell size. It can serve as an alternative length scale that could provide an assessment of the relative detonation sensitivity of combustible mixtures. The phenomenon itself is also of great fundamental significance containing all the essential mechanisms for failure and initiation.

Critical tube diameter of common fuels-air mixture in general can be determined roughly from the empirical correlation $d_c = 13\lambda$ where d_c is the critical tube diameter and λ is the characteristic detonation cell size [2]. Although this empirical correlation appears to be quite adequate for most gaseous hydrocarbon explosives, but it is shown to be invalid for mixtures with regular cell patterns such as mixtures with high argon dilution [3-5]. The correlations ranged from d_c = 25-30λ.

Studies have indicated that the detonation stability or cell regularity may play an important role in the detonation undergoing a sudden expansion into open space. Lee proposed two mechanisms, one local and one global for the diffracted wave to explain the failure and the breakdown of the 13λ rule [6]. The 13λ rule is generally applicable for mixtures with high degree of instability (i.e. mixtures highly sensitive to temperature) and the phenomenon is characterized by local explosion centers re-initiation mechanism. The breakdown of the 13λ correlation is ascribed to the regularity of the cell pattern, typical for highly argon diluted mixtures. The failure in this case occurs due to the global mechanism when the curvature of the attenuated detonation exceeds some critical value required for self-sustained propagation.

Detonation diffraction from a rectangular channel into free space, in which the aspect ratio $L/W \rightarrow \infty$, results in a cylindrical expansion of the detonation wave. In this case, only the width of the slot has an effect on the detonation and a critical thickness, W_c, can be defined in the same way as the critical diameter. In this study, critical thicknesses for the successful transformation of a planar to a cylindrical detonation are measured in different stable and unstable mixtures. A thin annular channel is used rather than a thin rectangular slot in order to avoid edge effects from the side wall. The height of the channel is small compared to the radius of the annulus such that radial curvature effects are negligible and a two-dimensional geometry can be realized. The objective of this work is to establish and

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examine the critical thickness correlation with cell size for different unstable and stable mixtures. The values of W_c/λ will also be compared to the predictions of failure mechanisms proposed by Lee [6]. If the mechanism of failure for stable mixtures is based on curvature, this should result in a relationship between d_c and W_c. The curvature of a cylindrical surface is half that of a spherical one, as curvature in one direction does not exist, therefore the theory expects $W_c \approx d_c/2$, a geometrical factor of two.

2 Experimental details

A 3.0 m long steel detonation tube with an inner diameter of 65 mm was used and the annular geometry was affixed to the end. A CJ detonation was first generated in the round steel tube which propagates for 2.64 m before it entered a 360 mm long annular channel inserted in the detonation tube. The annulus hubs have varying diameters to create different annular channel widths (i.e. w = 4.3 and 14.3 mm). These are all inserted into the annular channel section and are held in position by two sets of three equally spaced fins around the circumference. Their leading and trailing edges have all been chamfered to prevent any wave process from affecting the propagation of the detonation wave inside the channel. The end of the annular section was then connected to the expansion chamber. The chamber is 30 cm long and 15.24 cm inches in diameter. It has a window in the end flange to allow streak photographs to be taken. A sketch of the experimental apparatus is shown in figure 1.

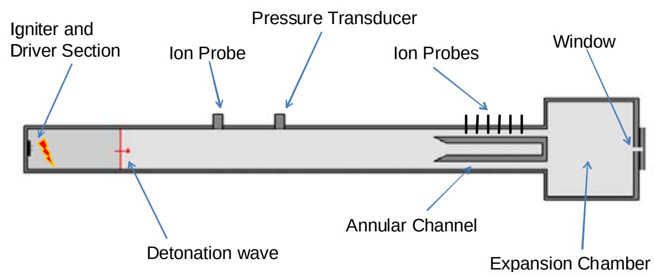

Figure 1. Sketch of experimental apparatus

Stoichiometric mixtures of acetylene-oxygen and acetylene-oxygen with 70% argon dilution were tested. The mixtures were prepared beforehand in a separate vessel by the method of partial pressures. The gases were allowed to mix in the vessel for at least 24 hr in order to ensure homogeneity. For any given experiment, the tube and chamber were initially evacuated to approximately 100 Pa. The entire apparatus was then filled from both ends to the desired initial pressure. The sensitivity of the mixtures was varied by the initial pressure. Direct initiation of a detonation was achieved by means of a high energy spark. In some cases, a long detonation driver section filled with stoichiometric acetylene-oxygen at 40 kPa was used to directly initiate the test mixture. The driver mixture was separated from the test mixture by a thin Mylar diaphragm.

Ionized probes were used in the detonation tube section to ensure a CJ detonation is obtained in the smooth round tube section. A rotating drum streak camera with a constant film speed of about 80 m/s was used to obtain the velocity of the diffracted wave propagating in the large chamber.

3 Results and discussion

Typical Streak photograph of a self-sustained detonation that is successfully re-established and of a failed diffracted wave that decayed abruptly upon the channel are shown in figures 2 and 3 for the undiluted and diluted cases, respectively. The waves under consideration are shown by the arrows. For undiluted mixtures, the diffracted wave existing from the annular channels are visible in the streak photograph and the criterion to define failure and successful transition is obtained by measuring the velocity of the diffracted wave. The successfully transitioned waves, shown by the green arrows, are much more luminescent and have a much steeper angle, thus are moving faster. The velocity of these waves was found to be on the order of V_{cj}. In the case of failure, the waves, shown by the red arrows, are much lighter and much slower, having speeds less than 1000 m/s and typically around 500 m/s.

In the argon diluted mixture, the expanding waves were not visible in the case of failure; the areas circled in red above have no visible markings where the waves should be seen. A wave that has successfully transitioned from planar to cylindrical is again shown by the green arrow above.

In all the streak pictures, the dark spot occurring at the wave intersection is where the cylindrically expanding waves have intersected at the axis of the annulus. Once this intersection occurs, more complex interactions are not considered in this investigation.

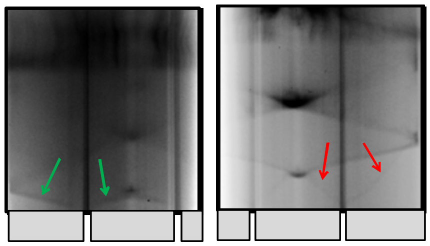

Figure 2. Typical streak photographs for successful transition and failure in undiluted mixtures.

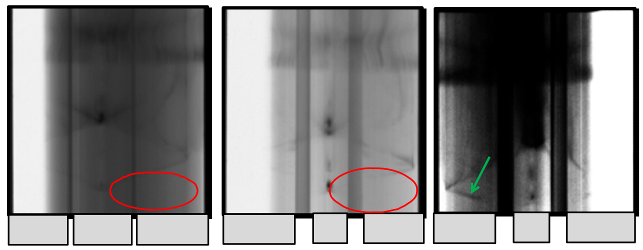

Figure 3. Typical streak photographs for successful transition and failure in Ar diluted mixtures.

The results for successful and unsuccessful transition from a planar detonation propagating in the annular channel to a cylindrical detonation in the large chamber are given in figure 4 as a function of initial pressures for different mixtures with and without Ar dilution. The critical pressure for each annulus and mixture lies between an adjacent failure (X) and successful transmission (O). No critical pressure was found for C_2H_2 + 2.5 O_2 + 70% Ar in the 4 mm channel as it lies above the maximum initial pressure accessible to the equipment used in this study. Table 1 summarizes these results.

Values of cell size λ with initial pressure for the two acetylene-oxygen mixture conditions are taken from [7, 8]. The resulting power-law best fit correlation between cell size and initial condition are given as:

$$\lambda[\text{mm}] = a \cdot (p_o[\text{kPa}])^b \begin{cases} a = 23.8 \quad b = \text{-}1.03 \text{ undiluted } 0\%\text{Ar} \\ a = 113.8 \quad b = \text{-}1.20 \text{ diluted } 70\%\text{Ar} \end{cases}$$

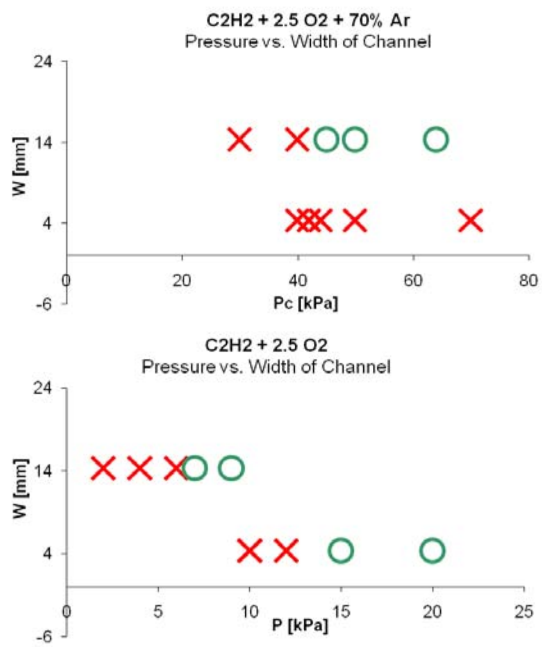

Figure 4. X denotes failure and O denotes successful transition.

Using the above correlation, the corresponding cell sizes λ for the critical pressures can be obtained and are shown in table 1. Table 1 also summarizes the critical thickness and critical tube diameter scaled by the cell size values and their ratio. Based on these results, some important observations can be made. For the results of unstable mixtures (undiluted C_2H_2-O_2 mixtures), the critical channel width over detonation cell size for the two channels used are found to be about 2.74 - 3.80. This result agrees well with that of Liu et al. [9] where they observed that as the expansion of the detonation approaches cylindrical form, namely for a rectangular channel with $L/W \rightarrow \infty$, $W_c/\lambda \approx 3$ for unstable mixtures. For highly argon diluted mixture with regular cellular pattern, one can observe that the critical tube diameter and the critical thickness differ by a factor of about 2. Hence, the current data supports a failure mechanism based on curvature given that a ratio of critical diameter to critical width near 2 arises for the stable mixture. In the undiluted case, this factor of two does not arise, suggesting that other mechanisms not based on curvature are playing a role.

Table 1: Summary of the experimental results

Mixtures	p_c	λ	w_c/λ	d_c/λ	d_c/w_c
C_2H_2-O_2					
Channel width = 14.3 mm	6 kPa	3.76 mm	3.80	13	3.42
Channel width = 4.3 mm	14 kPa	1.57 mm	2.74	13	4.74
C_2H_2-O_2-70%Ar					
Channel width = 14.3 mm	45 kPa	1.18 mm	12.1	25-30	2.07-2.48

4 Concluding remarks

Measurements of critical thickness in acetylene-oxygen mixtures with and without Argon dilution are performed in this study. It is found that for unstable mixture (without dilution), the correlation of critical thickness with detonation cell size is about $w_c/\lambda \sim 3$. As for stable mixtures (e.g. mixtures with high Ar dilution), the correlation appears to be about $w_c/\lambda \sim 12$.

The present study on the critical tube thickness provides some important observations on the two failure mechanism proposed by Lee. By investigating the critical thickness for diffracted detonations in explosive mixtures highly diluted with argon (where it has be found that the cellular instabilities play minor roles in the propagation mechanism), the present results support a curvature based global mechanism for failure in these stable mixtures. Comparison with experimental results in critical tube diameters appears to confirm that the relationship between the critical diameter and the critical thickness is very close to 2, corresponding to the geometrical factor of the curvature term between a spherical and cylindrical diverging wave.

References

[1] Lee JHS. (1984). Dynamic parameters of gaseous detonations. Ann. Rev. Fluid Mech. 16: 311.

[2] Mitrofanov VV, Soloukhin RI (1965) The diffraction of multifront detonation waves. Soviet Physics-Doklady 9(12): 1055.

[3] Moen I, Sulmistras A, Thomas GO, Bjerketvedt D, Thibault PA (1986) Influence of cellular regularity on the behavior of gaseous detonations. Prog. Astronautics and Aeronautics 106: 220.

[4] Shepherd JE, Moen I, Murray S, Thibault PI (1986) Analyses of the cellular structure of detonations. 21st Symp. Int. Combust. Proc. pp. 1649.

[5] Desbordes D, et al. (1993) Failure of classical dynamic parameters relationships in highly regular cellular detonation systems. Prog. in Astro. Aero. 153: 347

[6] Lee JHS (1996) On the critical tube diameter. In: J. Bowen, Editor, Dynamics of Exothermicity, Gordon and Breach, Amsterdam, Netherlands, pp. 321.

[7] Radulescu MI (2003) The Propagation and Failure Mechanism of Gaseous Detonations: Experiments in Porous-Walled Tubes. Ph.D. thesis, McGill University, Canada.

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

[9] Liu YK, Lee JH, Knystautas R (1984) Effect of geometry on the transmission of detonation through an orifice. Combust. flame, 56: 215.