Propagation Limits of Unstable Detonations in Thin Annular Channels

Anne Jesuthasan[1], Alexandra Camargo[1], Jean-Sébastien Grondin[1], Jenny Chao[2], Hoi Dick Ng[3] and John H.S. Lee[1]

[1]Department of Mechanical Engineering, McGill University, Montreal, H3A 2K6, Canada

[2]FM Global, Research Division, Norwood, USA

[3]Department of Mechanical and Industrial Engineering, Concordia University, Montreal, H3G 1M8, Canada

1 Introduction

Detonability limits refer to the conditions beyond which the self-sustained propagation of a detonation wave is no longer possible. Limits are a consequence of the influence of boundary conditions on the propagation mechanisms of the detonation wave. To elucidate the failure mechanism that are responsible for detonability limits, the propagation and failure of a detonation in two-dimensional annular channels have been investigated in the past for highly-argon diluted stoichiometric fuel-oxygen mixtures where cellular instabilities play minor roles in the propagation of a detonation [1]. For these "stable" detonations where the ZND structure has been shown to be a valid model, the limits can be ascribed to excessive velocity deficit due to flow divergence (i.e., curvature of the detonation front) caused by the negative displacement thickness of the boundary layer [2]. By solving the quasi-one-dimensional ZND equations with a curvature model and appropriate chemical kinetics, a criterion of the onset of the detonability limits can be described by the critical curvature and, thus, a maximum velocity deficit where no eigenvalue detonation velocity can be found. The detonability limits for stable detonations were found to be well-defined experimentally and agree well with the theoretical ZND prediction. No unstable near-limit phenomena such as galloping detonations were observed [1].

The description of the detonability limits in an "unstable" cellular detonation, however, is far more difficult because the effect of boundary conditions on the intrinsic unstable phenomenon must now be considered. In addition, a spectrum of near-limit phenomena such as spinning, galloping, pulsating and stuttering modes of a detonation renders the limit difficult to define. Existing limit criteria have generally been defined arbitrarily, and therefore, there is no operational definition of the detonability limits for highly unstable cellular detonations.

Nevertheless, in round tubes, the propagation mode of a spinning detonation has been considered as the limiting criterion. Based on this consideration, Lee [3] obtained a limit criterion for the minimum tube diameter $d^*=\lambda/\pi$ (where λ is the detonation cell size) by equating the time scale for the lowest transverse mode (i.e., single-headed spin) to the characteristic time scale of the chemical reactions. This criterion, however, cannot be applied to two-dimensional annular channels where the spin regime of a near-limit detonation is suppressed. A different criterion is required, and the mechanism leading to a unique operational definition of the detonability limits that accounts for the dual failure mechanisms of losses and of instabilities must be addressed.

Correspondence to: hoing@encs.concordia.ca

In this study, the propagation and failure of a detonation in methane–oxygen are investigated experimentally in thin annular channels. The aim of this study is to observe the various near-limit propagation modes in two-dimensional channels from velocity measurements. The degree of validity of the quasi-steady ZND model to define the limit of detonation propagation in unstable mixtures can be discussed, and the origin of the velocity deficit and other possible limit criteria will be explored using these experimental results.

2 Experimental details

A 2.64 m-long steel detonation tube with an inner diameter of 65 mm was used in the present investigation. A self-sustained CJ detonation was generated in the steel detonation tube and then entered a 360 mm-long annular-channel test section. The annular channel was created by inserting a copper tube into the end of the detonation tube. The leading edge of the copper tube was chamfered to prevent any wave process from affecting the propagation of the detonation wave in the test section. Experiments were conducted using two different annular channel heights: $w = 2.2$ and 4.3 mm. A sketch of the experimental apparatus is shown in Fig. 1.

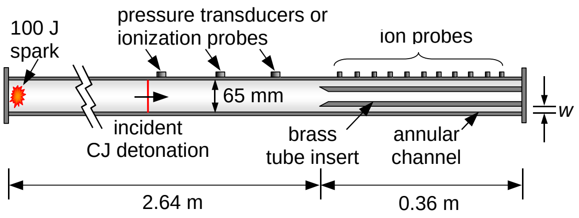

Figure 1: Schematic of experimental apparatus.

A stoichiometric mixture of methane-oxygen was tested, and the sensitivity was varied by the initial pressure. The mixture was 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 hours in order to ensure homogeneity. For any given experiment, the detonation tube was initially evacuated to approximately 100 Pa and then filled to the desired initial pressure. Direct initiation of the incident CJ detonation in the upstream section was achieved via a high energy spark.

Ionization probes 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 only using ionization probes, which permitted the trajectory of the wave front to be determined.

3 Quasi-steady ZND theoretical analysis

For comparison with the experimental data, results from the quasi-one-dimensional ZND structure equations with a curvature term and detailed chemical kinetics for the reactions are also obtained. The quasi-steady ZND model includes the effect of the viscous boundary layer following the pioneering work of Fay [1, 2, 4]. The boundary layer tends to remove mass from the free stream flow and this is accounted for by the flow of an inviscid fluid through an expanding nozzle where the cross-sectional area change is related to the displacement thickness of the boundary layer developed behind the shock front. The effective cross-sectional area of the channel at any point is given by $A = w + 2\delta^*$. The area change and the mass displacement thickness δ^* are given as:

$$\xi(x) = \frac{1}{A}\frac{dA}{dx} = \frac{2}{w+2\delta^*}\frac{d\delta^*}{dx} \qquad \delta^* = 0.22 \cdot x^{0.8}\left(\frac{\mu}{\rho_o D}\right)^{0.2}$$

The complete ZND model equations together with the flow divergence term in the conservation of mass equation and detailed chemistry model [5] are solved numerically with the CHEMKIN II package. Following the methodology discussed in [1,5,6], different detonation velocities were iterated to determine numerically the eigenvalue solution satisfying the generalized CJ criterion when the flow condition attained $M = 1$ in a continuous regular transition. (i.e. when the flow is choked in the frame of reference of the leading shock, the rate of chemical energy release must balance the rate of mass divergence). The limit is achieve when the velocity deficits exceeds a certain maximum values (or a certain critical curvature of the front) and no steady ZND solution can be obtained. For both the acetylene-oxygen-argon and methane-oxygen mixtures, the UC San Diego reaction kinetic mechanism was used.

3 Results and discussion

Typical trajectories of incident detonations entering the annular-channel test section are shown in Fig. 1 for four different initial pressures of 1, 3, 10 and 40 kPa. In all cases, the velocity of the incident detonation in the smooth tube section is measured to be around 2110 to 2350 m/s, which are very close to the theoretical CJ detonation velocities (V_{CJ}) of 2192, 2238, 2290, and 2350 m/s for 1, 3, 10 and 40 kPa, respectively. For the case of $p_o = 40$ kPa, it can be seen that the incident CJ detonation in the smooth tube section enters the annular channel section at a velocity of about 2350 m/s and continues to propagate in the thin annular channel at a slightly lower velocity of 2250 m/s (about 0.96 V_{CJ}).

When the initial pressure is decreased to $p_o = 10$ kPa, a detonation traveling at a velocity of 2030 m/s is observed in the annular test section for a distance of about 220 mm (or 51 channel heights). After 51 channel heights, the detonation decays to a high speed turbulent deflagration with a velocity of 1260 m/s, which corresponds to about half the theoretical CJ detonation velocity as well as the sound speed in the combustion products. This high speed turbulent deflagration continues to propagate at 0.5 V_{CJ} for the remainder of the test section; it is neither observed to decay any further below the 0.5 V_{CJ} value nor transit to detonation.

As the initial pressure is decreased further, the onset of the detonability limit, manifested by the failure of the detonation in the annular channel, is not observed. Instead, unstable galloping phenomenon occurs: At $p_o = 3.0$ kPa, the incident detonation decays to about 1720 m/s soon after it enters the annular channel. After a distance of about 145 mm (or 33 channel heights), the detonation is reinitiated and propagates at 2590 m/s for a distance of about 17 channel heights (75 mm) after which the detonation decays to 1200 m/s or 0.5 V_{CJ} for the remainder of the annular channel (about 41 channel heights or 175 mm). Similarly, at $p_o = 1.0$ kPa, the propagation of the detonation within the annular channel test section is characterized by the cyclical failure and reinitiation of the detonation wave.

From the experimental trajectories, the velocities of the combustion wave inside the annular channel are extracted and represented in Fig. 2 for different initial pressures and channel widths. The theoretical velocities from the quasi-steady ZND analysis are also plotted for comparison. For the channel height of $w = 4.3$ mm, the theoretical calculation predicts the detonability limit to be about 25 kPa. However, complete failure of the detonation wave in the annular channel is not observed in the experiments, even at initial pressures as low as $p_o = 1.0$ kPa. For a smaller channel height of $w = 2.2$ mm, the same phenomenon is observed. The theoretical calculations predict that failure due to momentum losses should occur below 44 kPa; however, a galloping detonation can be sustained in the annular channel at initial pressures as low as $p_o = 1.0$ kPa.

It is interesting to note that near-limit behaviour in methane-oxygen mixtures departs significantly from that observed previously in stable mixtures with large amounts of argon dilution [1]. This clearly indicates that the failure mechanism is not is not only caused by the curvature; the high intrinsic instability in the methane-oxygen mixture provides a mechanism to maintain detonation propagation in small channels.

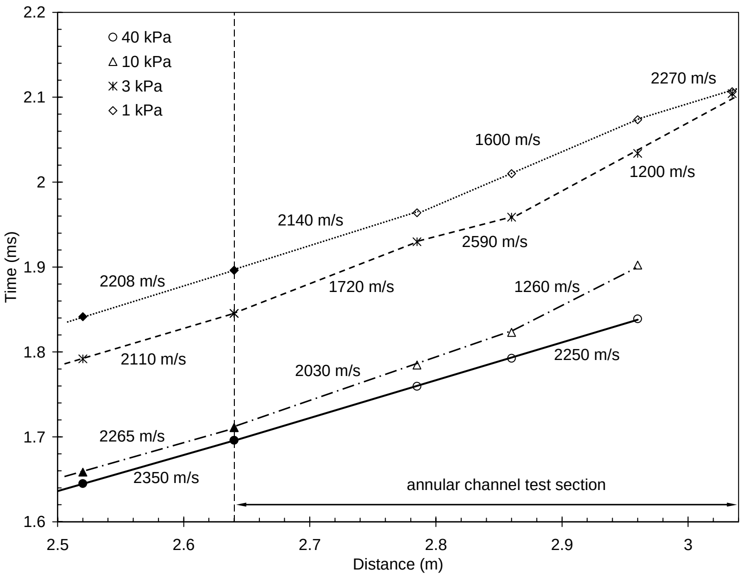

Figure 2. Typical trajectories of detonation propagation in the 4.3 mm annular channel section for $CH_4 + 2O_2$.

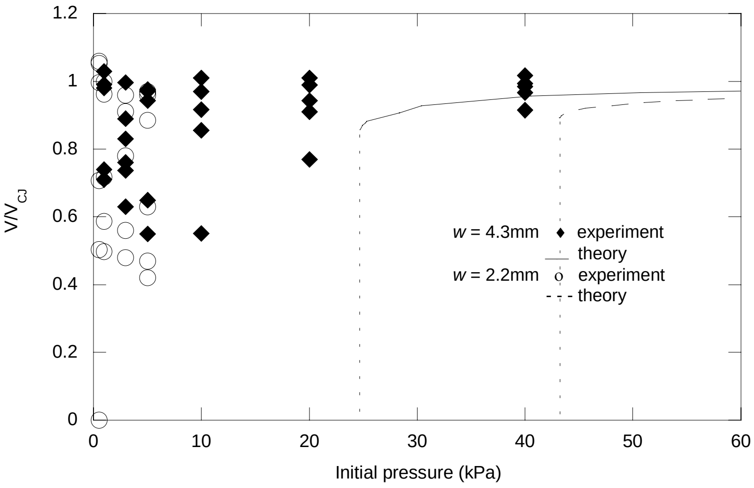

Figure 3. Comparison of theoretical curvature model with experimental results for $CH_4 + 2O_2$.

Acknowledgment

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

References

[1] Chao J, Ng HD, Lee JHS. (2009) Proc. Combust. Inst. 32: 2349.
[2] Fay JA. (1959) Phys. Fluids 2: 283.
[3] Lee JHS, Knystautas R, Freiman A. (1984) Combust. Flame. 56: 227.
[4] Dove JE, Scroggie BJ, Semerjian H (1974) Acta Astro. 1: 345.
[5] Klein R, Krok JC, Shepherd JE (1995) GALCIT FM 95-04, California Institute of Technology.
[6] Radulescu MI, Lee JHS (2002) Combust. Flame 131(1-2): 29.