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Velocity fluctuation near the detonation limits

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ABSTRACT

In this study, the velocity fluctuation near the detonation limits is investigated experimentally. Five explosive mixtures in five different diameter tubes were used and the choice of the mixtures included those considered as "stable" with regular cellular pattern and "unstable" with highly irregular cellular pattern. Photodiodes spaced at regular intervals along the tube were used to measure the detonation velocity. Piezoelectric transducers were also used to record the pressure profiles. Smoked foils were used to register the cellular detonation structure. Away from the limits, the detonation is found to propagate at a steady velocity throughout the length of the tube and the fluctuations of the local velocity are generally small. For stable mixtures with high argon dilution, the onset of the detonation limits is indicated by an abrupt drop in the detonation velocity to about $0.4V_{CJ}$ after a short distance of travel. The detonation may continue to propagate at this low velocity before decaying eventually to a deflagration wave. For deflagrations the optical detector sometimes failed to register a signal due to low luminosity of the front. In unstable mixtures, galloping detonations are observed only in small diameter tubes (e.g., D = 12.7, 3.2 and 1.5 mm). A large number of fairly reproducible cycles of galloping detonations can be observed in very small diameter tubes. In large diameter tubes (e.g., D = 31.7 and 50.8 mm), no galloping detonations are observed in all stable and unstable mixtures. For stable mixtures, no galloping detonations are observed even in small diameter tubes of D = 3.2 and 1.5 mm. Smoked foils records show that the cellular detonation structure changes from multi-headed to single-headed spin as the limit is approached. In a galloping detonation cycle, a decay from multi-headed to single-headed detonation is observed. However, the cellular structure vanishes for further decay of the galloping detonation to the low velocity phase of the galloping cycle. Although galloping detonations could be considered to define the boundary for detonation limits, this definition lacks generality since galloping detonations are not always observed in all mixtures and in all tube diameters. Thus the onset of single-headed spin is perhaps the most appropriate criterion of the detonation limits in tubes.

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1. Introduction

Detonation waves are intrinsically unstable with a transient cellular structure formed by an ensemble of interacting transverse waves. Thus the local velocity of the detonation front fluctuates about a mean value of the order of the CJ velocity with a frequency inversely proportional to the cell size. Further decrease in mixture sensitivity leads to the enlargement of the cell size (or transverse wave spacing) and the detonation limit is approached, i.e., conditions outside of which the detonation wave fails to propagate.

The detonation velocity near the limits is reported in a previous paper [1]. The velocity is a value averaged over the distance of propagation of the detonation wave. However near failure of the detonation, the velocity fluctuations become increasingly large rendering the averaged velocity of doubtful significance. In fact, the failure mechanism is obscured in the averaging process since it is the instability itself that is responsible for the propagation of the detonation wave. Therefore, to understand detonation limits, one must investigate the instability of the front as the limits are approached. The present study emphasizes the instability of the front as the limits are approached.

It is well known that far from the limits the frequency of the transverse instability is high (or equivalently the cell size is small); the instability tends toward lower modes and eventually single-headed spinning detonation is reached. While the scale of the frontal instability is of the same order as the tube diameter ($\lambda \approx \pi \cdot D$), in

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fact the onset of single-headed spinning detonation had been chosen to define the detonation limits by various investigator, e.g., [2–4]. The single-headed spinning detonation represents the lowest mode of transverse instability of the detonation front. However, numerous investigators have reported longitudinal instability in the form of "stuttering" and galloping detonations; see [4–9] and references therein. The velocity fluctuation of these longitudinal instabilities ranges from as low as $0.4V_{CJ}$ to $1.2V_{CJ}$ and the detonation of the low velocity phase (i.e., $0.4V_{CJ}$) can be very long. A galloping cycle is generally over 300 tube diameters, yet the averaged value of the velocity for galloping detonations is found to be still close to the CJ value. Thus, it appears that galloping detonation waves have similar apparent characteristics of a genuine detonation and that the limits should be extended beyond the spinning mode to include these longitudinal unstable detonations. In fact, a number of investigators have suggested that galloping detonation be considered as boundary for the onset of detonation limits. Beyond galloping detonations, the detonation velocity decayed to about $0.4V_{CJ}$ and this is generally referred to as "low-velocity detonation" or sometimes it is also called high-speed deflagration. Whether these quasi-steady, low-velocity detonations or fast deflagrations can be considered as detonations is not clear. In addition, little is known about their structures. The mechanisms of galloping and low-velocity detonations are not understood and relatively little detailed study of these unstable detonations waves with large fluctuations had been made. It appears that this class of longitudinal unstable detonations is crucial toward understanding of the failure mechanisms at the detonation limits since they occur just prior to failure.

In our continuing effort to understand the detonation limits phenomenon, the present study focuses particularly on the velocity fluctuations just prior to failure. Not all detonations in different mixtures and tube diameters exhibit large fluctuations near the limits. Hence in the present investigation, a variety of mixtures, from the high argon-diluted "stable" mixtures to the "unstable" mixture of methane–oxygen, propane–oxygen and fuel–N_2O as oxidizer are studied. The detonation stability of a mixture is typically assessed by its chemical activation energy or more recently by the stability parameter χ – defined by the activation energy of the induction zone multiplied by the ratio of induction zone to the exothermic heat release length, see [10,11]. An unstable mixture (e.g., undiluted hydrocarbon fuel mixture) usually has a very large value of activation energy (or stability parameter χ) and the detonation cellular structure in the unstable mixture is observed to be irregular. For a stable mixture, the chemical reaction is less sensitive to any temperature fluctuation. In other words, it has a low activation energy and also a larger heat release region that results in a low value of the stability parameter χ. The detonation structure in stable mixtures is piecewise laminar without any sub-scale instability at the detonation front. Such mixture can be formed with large amount of argon dilution [12].

Since the cycle of the unstable oscillations can cover a large distance of propagation (e.g., hundreds of tube diameter), small diameter tubes as low as 1.5 mm diameter have to be used to ensure propagation over hundreds of tube diameters. Velocity measurement is the main diagnostic used and where possible smoked foils were used to record the cellular detonation structure.

2. Experimental setup

The detonation tube used in the present study consists of a 1.3 m long steel driver section with a diameter of 65 mm. The transparent polycarbonate test tubes of various diameters were attached to the end of the driver tube. Five different diameters, D = 1.5, 3.2, 12.7. 31.7 and 50.8 mm, were used in the present study with total tube length L = 2438, 2438, 4118, 4118, 4118 mm and thickness T = 0.8, 1.6, 3.2, 3.2, 3.2 mm, respectively. The total length L of the test section was obtained by connecting several same diameter tubes of about 200 mm long using Swagelok tube fittings. Care was exercised to connect smoothly the tubes to avoid any influence of the joint. Detonation was initiated by a high energy spark discharge. A short length of Shchelkin spiral was also inserted downstream of the spark plug to promote detonation formation. For experiments with the small diameter tubes of 1.5 mm and 3.2 mm in diameter, a driver section of 25.4 mm diameter and 1.5 m long with a much more sensitive mixture was used to facilitate the detonation formation and its initial propagation in the test gas before the boundary effect started to take place. A schematic of the experimental apparatus is shown in Fig. 1a.

Five explosives mixtures, i.e., $C_2H_2 + 2.5O_2 + 85\%Ar$, $C_2H_2 + 2.5O_2 + 70\%Ar$, $C_2H_2 + 5N_2O$, $C_3H_8 + 5O_2$, $CH_4 + 2O_2$ were used and the choice include those mixtures considered as "stable" with regular cellular pattern and "unstable" with highly irregular cell pattern. In general, stoichiometric mixtures of acetylene-oxygen with high argon dilution of 85% and 75% argon dilution are considered as "stable" mixture whereas the other three mixtures are considered as "unstable" with irregular cell pattern. The explosive mixtures of the desired composition were prepared via partial pressure in separate gas bottles. The gases were allowed to mix in the vessel by diffusion for at least 24 h in order to ensure homogeneity prior to being used. For any given experiment, the detonation tube was evacuated to at least 10 Pa. The entire apparatus was then filled from both ends to the desired initial pressure. A gas control panel, equipped with an Omega pressure transducer (PX02-I) and a Newport digital meter (IDP) was used to monitor the pressure for both mixture preparation and the experiment.

Two piezoelectric pressure transducers (PCB 113A24) were mounted on the steel driver section in order to verify that a CJ detonation was obtained prior to its transmission to the test section tube. Fiber optics of 2 mm in diameter connected to a photodiode

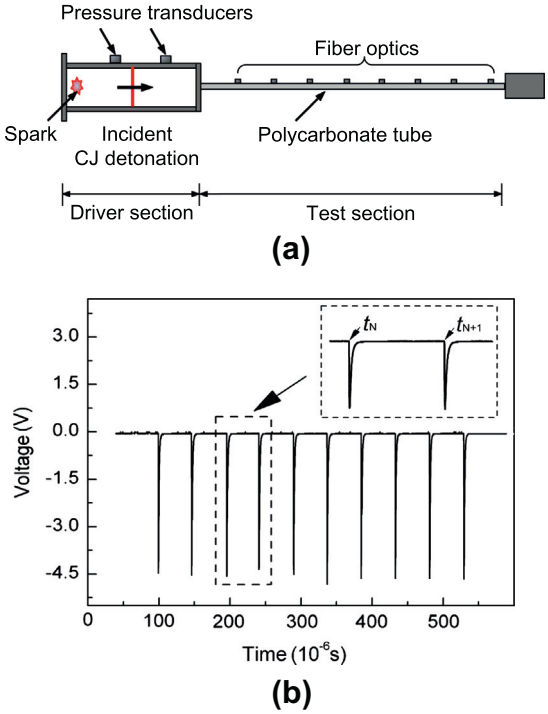

Fig. 1. (a) A schematic of the experimental apparatus and (b) sample signals from the optical detectors.

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