Velocity Fluctuation Near the Detonation Limits

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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) as the detonation limit is approached (i.e., conditions outside of which the detonation fails to propagate).

The detonation velocity near the limits has been 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. Thus to understand detonation limits, one must investigate the instability of the front as the limits are approached, which is the main focus of the present study.

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 where the scale of the frontal instability is of the same order as the tube diameter ($\lambda \approx \pi d$). In fact, the onset of single headed spinning detonation had been chosen to define the detonation limits by various investigators, e.g., [2-4]. The single headed spinning detonation represents the lowest mode of transverse instability of the detonation front. However, numerous investigators have also reported longitudinal instability in the form of "stuttering" and galloping detonations; see [5]. 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 can be over 100 tube diameter - yet the averaged value of the velocity for these stuttering and galloping detonations is still close to the CJ value. Thus, it seems reasonable to consider these stuttering and galloping detonation waves as "bona fide" detonations and that the limits should extend beyond the spinning mode to include these longitudinal unstable detonations. Beyond galloping detonations so-called "low velocity detonations" (or sometimes referred to as fast deflagrations) where quasi-steady velocity of the order of $0.4V_{CJ}$ have also been reported. Whether these quasi-steady low velocity detonations or fast deflagrations can be considered as detonations is not clear. The mechanisms of galloping and low-velocity detonations are not well understood and relatively little detailed study of these unstable large fluctuation of the detonation wave had been made. In fact, previous studies of this class of longitudinal unstable waves are rather limited to one mixture in a given diameter tube. However, it appears that this class of longitudinal unstable waves is crucial towards understanding of the mechanisms of detonation limits.

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In our continuing effort to understand the detonation limits phenomenon, the present study focuses particularly on the velocity fluctuations just prior to failure. Velocity near the detonation limits in a variety of mixtures, from large argon-diluted "stable" mixtures to the "unstable" mixture of methane-oxygen, propane-oxygen and fuel-N_2O as oxidizer are reported in this paper. Since the cycle of unstable oscillations covers a large distance of propagation (i.e. hundreds of tube diameter), small diameter tubes as low as (1.5 mm diameter) have to be used. Unfortunately apart from velocity measurements there is little diagnostics possible to make detailed observations of the structure of the unstable wave in an oscillation cycle particularly in small diameter tube.

2 Experimental setup

The detonation tube used in the present study consists of a steel driver section 65 mm diameter and 1.3 m long. The polycarbonate test tube of various diameters is attached to the end of the driver tube. Five different diameters, D = 1.5, 3.175, 12.7. 31.75 and 50.8 mm, were used in the present study with total tube length L = 2438, 2438, 4118, 4118, 4118 mm, respectively. Detonation was initiated by a high energy spark discharge and a short length of Shchelkin spiral was also inserted downstream of the spark plug to promote detonation initiation. For experiments with the small diameter tubes of 1.5 mm and 3.175 mm in diameter, a driver section of 25.4 mm diameter and 1.5 m long filled with a more sensitive mixture (stoichiometric C_2H_2-O_2) was used to facilitate detonation initiation in the driver section and to ensure a CJ wave was formed prior to the detonation wave entering the test section. A schematic of the experimental apparatus is shown in Fig. 1a.

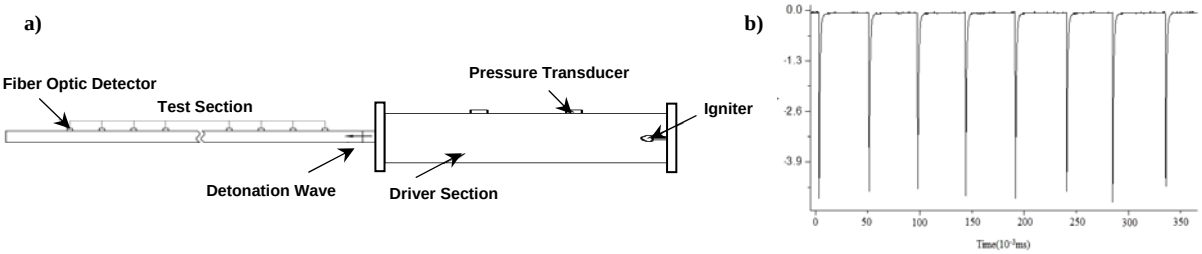

Figure 1. a) A schematic of the experimental apparatus; and b) a sample signals from the optical detectors

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 includes 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 where as the other four mixtures are considered as "unstable" mixtures. The explosive mixtures of the desired composition were prepared via partial pressure method and allowed to mix for at least 24 hours prior to being used. Piezoelectric transducers were used for pressure measurement and for the measurement of detonation velocity, 2 mm diameter fiber optics were spaced periodically along the entire length of the test section. Detonation velocity was determined from the time-of-arrival of the detonation at various optical probe locations. Typical output from the optical detectors is shown in Fig. 1b.

3 Results and discussions

For a given mixture and tube diameter, the detonation limits are approached by progressive decreasing the initial pressure p_o. Above the limits, the detonation velocity remains fairly constant throughout the distance of propagation. Although the local velocity shows increasing fluctuations towards the limits, these are sufficiently small and a meaningful averaged velocity can be obtained. The average velocity is found to range from 0.8 $V_{CJ} \leq V_{avg} \leq V_{CJ}$ and depends slightly on tube diameter and the mixture.

For stable mixtures (e.g., C_2H_2+2.5O_2 with 70% and 85% argon dilution), in which the cellular detonation front is rather regular, the onset of limits is indicated by an abrupt drop in the detonation

velocity to a value less than $0.4V_{CJ}$ after a short distance of travel. The detonation remains at this low velocity and in some cases, slight acceleration can be observed before it drops further. The optical probes then fail to register reproducibly for the low velocity deflagrations due to insufficient luminosity. The slight acceleration of the low velocity detonation that is observed in the smaller diameter tube (e.g., 3.17 mm) suggests that the re-acceleration may be due to wall boundary layer effect. In bigger diameter tubes (i.e., 31 mm, 50 mm), no re-acceleration of this low velocity detonation is observed (see Fig. 2e).

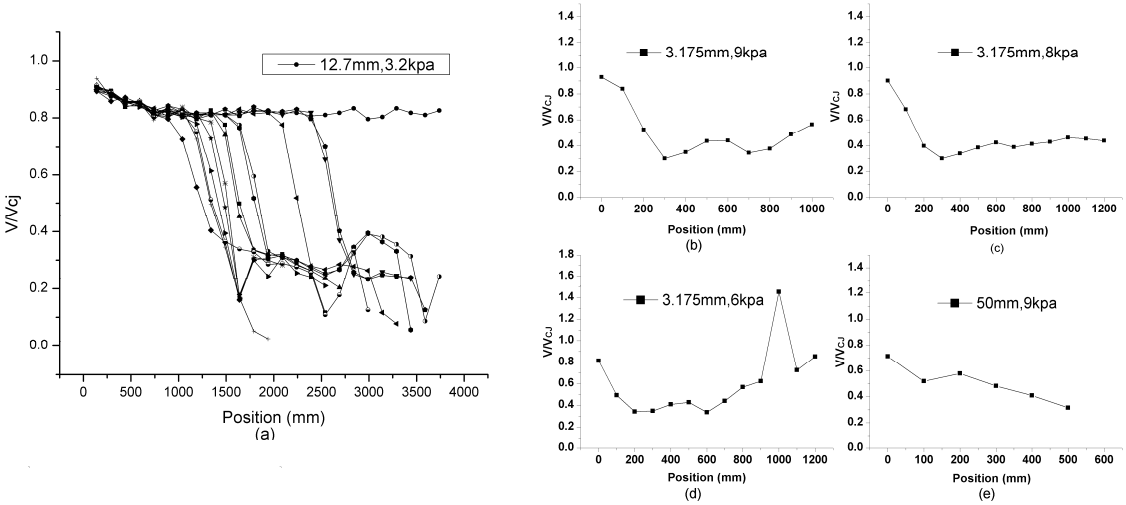

Figure 2. Velocity results for stoichiometric C_2H_2-O_2-70%Ar mixture. a) D = 12.7 mm (including data from several shots to show the repeatability of results); b) to d) D = 3.175 mm and e) D = 50 mm

For an unstable mixture like C_3H_8+$5O_2$, the behavior of the detonation at failure is more interesting. Figure 3a presents some results for the largest tube diameter D = 50 mm. Just above the limiting pressure, the detonation velocity on average is fairly constant throughout the length of the tube, although some small fluctuations can be seen. The velocity is of the order of $V_{avg} \approx 0.9V_{CJ}$. At the onset of detonation failure, the detonation velocity decreases continuously. Similar to the argon-diluted mixture, galloping detonations are not observed in larger diameter tubes (i.e., 31 mm and 50 mm). Past the limiting pressure the detonation velocity decays continuously. The near-limit behavior of the detonation becomes more interesting for smaller tube diameters and large velocity fluctuations can be observed. A further decrease in the initial pressure led to the onset of galloping and low velocity detonations ($V \sim 0.4V_{CJ}$). A number of galloping cycles can be observed in the smallest diameter tube (i.e., 1.5 mm). In 3.175 and 12.7 mm diameter tubes, only one or two cycles of galloping detonation were observed for C_3H_8+$5O_2$.

For the unstable mixture of CH_4+$2O_2$, similar behavior as C_3H_8+$5O_2$ is observed (see Figs. 4). However methane-oxygen mixtures appear to be more unstable than propane in that prior to the limiting pressure, larger velocity fluctuations are already observed. In some cases, the detonation shows large burst of fluctuation before returning to its value of ~$0.8V_{CJ}$. At the limit itself, the detonation velocity decreases to a low value of about $0.6V_{CJ}$, and in the smallest diameter tube of 1.5 mm many cycles of galloping detonations are observed. For the unstable mixture of CH_4-O_2, the galloping mode can be observed within a large pressure range. Note that in the larger diameter tubes, both unstable mixtures of propane and methane do not show galloping detonations.

It is also worth noting that in some cases of stoichiometric C_3H_8-O_2 and CH_4-O_2 mixtures in the D = 3 mm tube, the detonation velocity dropped to a value of around ~0.6 V_{CJ} (see Fig. 5) before it decays to a deflagration when the initial pressure is further decreased. This low velocity detonation may be interpreted as a deflagration with the flame front propagating at the same velocity as the precursor shock. This is made possible by the displacement effect of the boundary layer behind the shock, a mechanism suggested by Manzhalei [6].

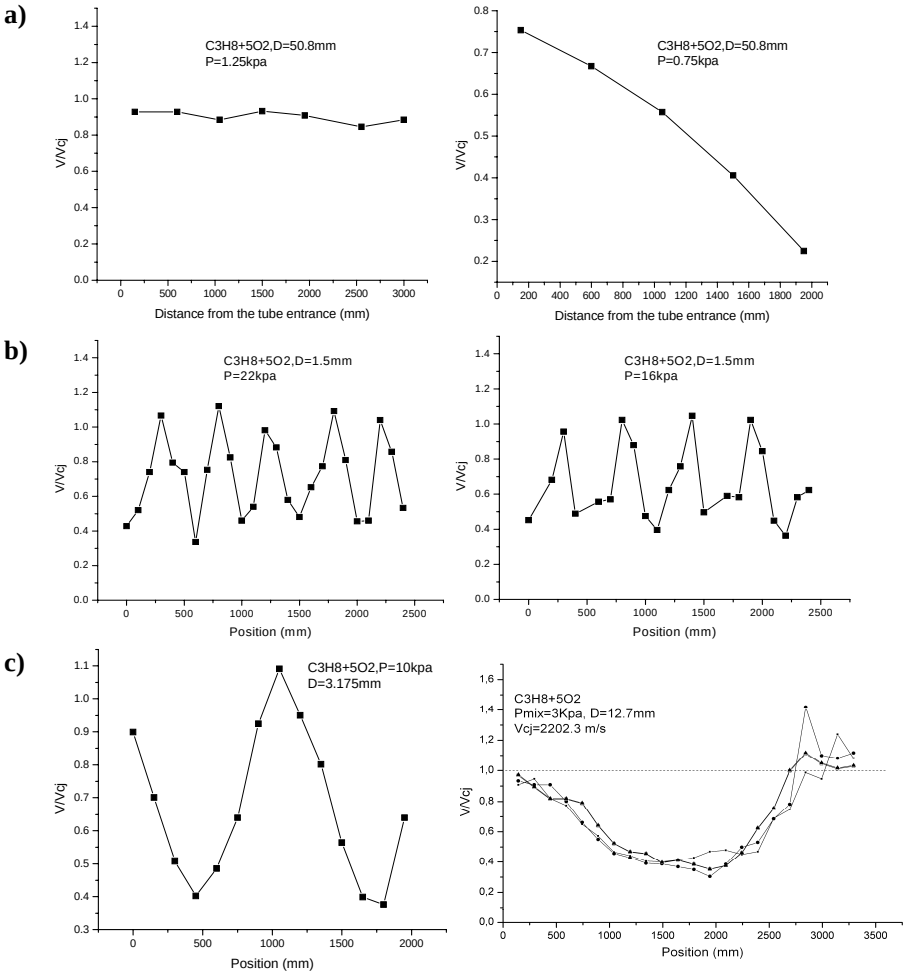

Figure 3. Velocity results for stoichiometric C_3H_8-O_2 mixture

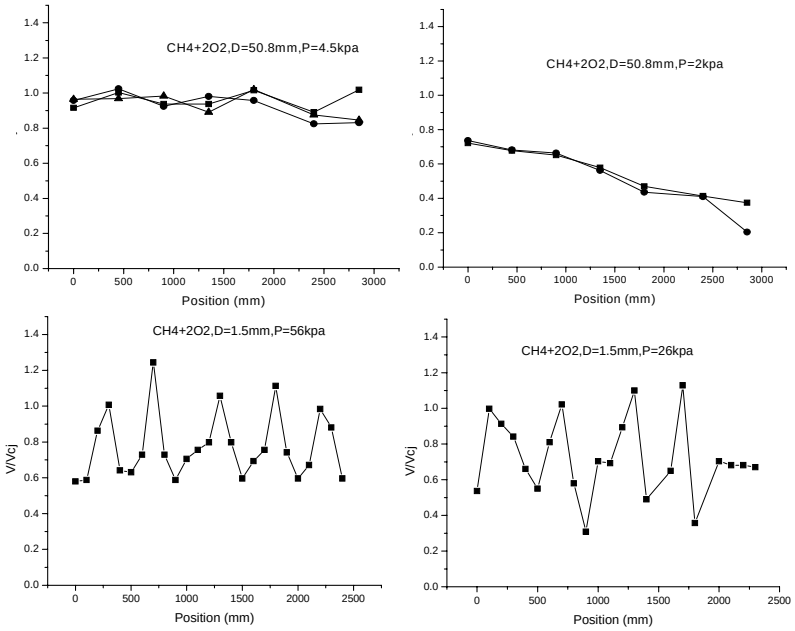

Figure 4. Velocity results for stoichiometric CH_4-O_2 mixture with D = 50 and 1.5 mm

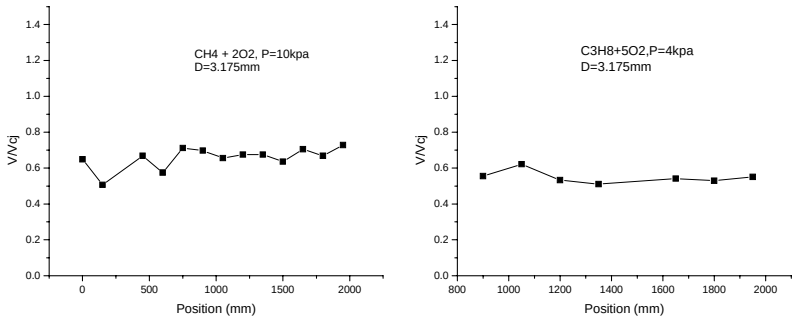

Figure 5.Velocity results for stoichiometric C_3H_8-O_2 and CH_4-O_2 mixtures with D = 3 mm

For stoichiometric C_2H_2-N_2O mixture, similar behaviors as in the case with C_3H_8-O_2 and CH_4-O_2 can be observed. This indicates that mixtures with N_2O as oxidizer are also unstable as C_3H_8-O_2 and CH_4-O_2. In large diameters tubes, again no galloping mode was observed near the limit, although DDT is sometimes observed when the wave attempts to re-accelerate back to a detonation. However, galloping detonations are observed for the two smallest tube diameters of D = 3 and 1.5 mm.

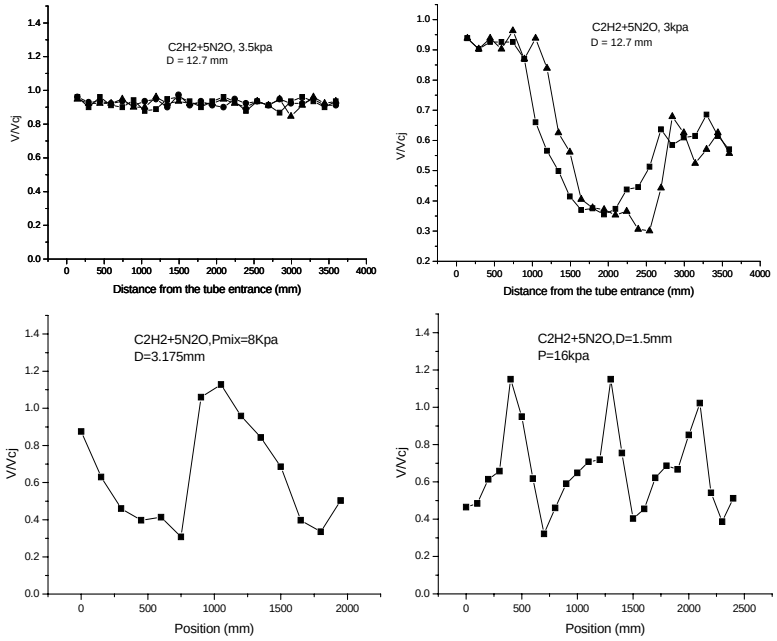

Figure 6.Velocity results for stoichiometric C_2H_2-N_2O mixture with different tube diameters

4 Concluding remarks

In this study the velocity fluctuation near the detonation limit of five explosive mixtures in various diameter tubes have been investigated. The following general conclusions can be drawn:

- Away from the limits, the detonation propagates at a steady velocity with small local fluctuations. The velocity is observed to be in the range of $0.8V_{CJ} \le V \le V_{CJ}$. The velocity deficit increases with decreasing tube diameter. Qualitative behavior of the velocity deficit can be described by the Fay-Dabora model [7]. This agrees with the results of previous studies, e.g., [1, 8, 9].
- At the limit, the detonation fails, as evidenced by the abrupt drop in its velocity after a short distance of propagation. The detonation velocity decreased to a low value ranging from $0.4V_{CJ} \le V \le V_{CJ}$. For "stable" mixtures (e.g., C_2H_2+2.5O_2+70%Ar, C_2H_2+2.5O_2+85%Ar), the detonation continues to decay to deflagrations where the optical detector failed to register a signal due to their weak luminosity. In small diameter tubes (i.e., D = 1.5 and 3.175 mm) the detonation appears to

be able to maintain propagation at a low velocity of ~ $0.4V_{CJ}$ for long distances. In some cases, a slightly acceleration can even be observed. This suggests that wall boundary layer effect plays a role in the propagation of low velocity detonation as suggested by Vasil'ev [10]. The slight acceleration observed may be due to the effect of turbulence from the boundary layer influencing the combustion front behind the precursor shock of the low velocity detonation. The absence of low velocity detonation in larger diameter tubes supports the view that boundary layer is responsible for the sustained propagation of low velocity detonation.

- Galloping detonations are observed in the "unstable" mixtures of $C_3H_8+5O_2$, CH_4+2O_2, $C_2H_2+5N_2O$ where a number of galloping cycles is recorded in small diameter tubes (1.5 and 3.175 mm). In large diameter tubes, only a couple of cycles are observed usually for the length of the detonation tube used. In even larger diameter tubes only an acceleration of the low velocity detonation is sometimes observed suggesting the tendency of the detonation to develop a galloping cycle. Galloping detonations are due to gasdynamic effects and in the early observation of galloping detonations by Mooradian & Gordon [11], they suggested that galloping detonation is based on a mechanism proposed by Brinkley & Richardson [12], i.e., a pocket of shocked mixture undergoing induction process is left behind the "sub-Chapman Jouguet" detonation which later exploded generating a compression pulse which catches up to the leading shock and brings it to the overdriven velocity phase of the galloping cycle. This mechanism is in contrast to the suggestion by Oppenheim [13] who draws the similarity of the acceleration phase of the galloping detonation to the regular onset of detonation processes in DDT. The smoked foil records of Vasil'ev [10] of galloping detonation also indicate that the re-acceleration to the overdriven state is due to gasdynamics processes rather than the "explosion center" that lead to the abrupt onset of detonation and DDT. The formation of detonation due to compression pulses catching up to the precursor shock is also illustrated in the monograph by Lee [4].
- The fact that galloping detonations are only observed in unstable mixtures and in smaller diameter tubes perhaps suggests that galloping detonation is a consequence of the boundary layer. However, it should be noted that galloping detonations were also observed in fairly large tubes by Edwards et al. [14], Lee et al. [5] and Haloua et al. [15]. Thus it is inconclusive that galloping detonation is due to the boundary layer effect created by the very small tubes.

It may be concluded that galloping detonations could define the detonation limits. Nevertheless, galloping detonations are not always observed in all mixtures and in all tube diameters. Thus the criterion based on the onset of single-headed spin seems to be still a more general definition of the detonation limits in tubes.

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