The Failure Mechanism of Detonations Propagating in Porous Wall Tubes

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Introduction

In general, gaseous detonation waves exhibit a complex and unsteady reaction zone structure consisting of mutually interacting transverse shock waves, shear layers and density gradients. Due to the unsteady nature of the frontal structure, only part of the gas is ignited behind the leading shock (Mitrofanov, 1994). The ignition of the remaining unreacted gas is effected by the successive interactions between the transverse shocks, shear layers and density interfaces. As Lee pointed out, these interactions provide a powerful mechanism of generating high burning rates by generating vorticity and increasing the mixing between gases at different stages of their reaction (Lee, 1991). In this sense, the ignition mechanism in real detonations can be viewed as a combination of the classical mechanism of ignition by shock compression supplemented by the intense mixing due to transverse wave interactions.

To elucidate the relative importance of these two simultaneous ignition mechanisms occurring in real detonations, Dupré et al. (1986), Vasiliev (1994), and Teodorczyk et al. (1995) conducted experiments in acoustically absorbing tubes to eliminate the transverse wave system. They found that when a fully established detonation enters the damping section, the detonation fails and results in a de-coupled shock-reaction zone complex. Neglecting other losses to the tube walls, these studies concluded that transverse waves, and their interactions, are essential to the propagation of real detonations. However, these studies have not measured the details of the attenuation process, as to support their conclusions.

In particular, it is unclear in these damping experiments whether the detonation fails as a result of the attenuation of the transverse shocks alone, or by the velocity deficit mechanism due to curvature from mass divergence. For example, in damping experiments with soft materials (e.g. rubber and foam), transverse waves are weakened upon reflection, but the net overpressure between the reaction zone and the compliant wall also leads to the deformation of the wall. This results in lateral mass divergence, which generates expansion waves and results in a decrease in the average pressure in the reaction zone. As a result of this lateral mass divergence, the lead shock is weakened and curved, and reactions could quench altogether (Fay, 1959). Similarly, as transverse waves reflect off a rigid and porous damping material, gas leaks to the porous wall, which causes expansion waves and eventually can lead to eventual detonation failure. It becomes clear from the above discussion that, in the previous experiments, the two failure mechanisms of transverse wave attenuation and leading shock weakening by mass divergence operate simultaneously. Little can be said about the role of transverse wave structure alone before the relative importance of these two failure mechanisms is clarified.

The present study will address these issues by a detailed study of the attenuation process of detonations propagating in porous walled tubes. In order to assess the importance of global failure by mass divergence and failure by transverse wave attenuation, reference experiments will be first performed in mixtures that can only fail by the mass divergence mechanism. Experimentally, such conditions can be achieved in stable detonations that rely only on leading shock compression as ignition mechanism. Such stable mixtures can be obtained by large dilutions with a heavy mono-atomic gas such Argon. The large dilution with Argon significantly reduces the specific heats of the gas mixture, thus rendering the reaction rates less sensitive to temperature variations. The resulting stable detonations become essentially one-dimensional and exhibit only weak transverse waves that do not contribute to gas ignition (Strehlow, 1967). These artificially stable 1D detonations will serve to gauge the importance of the mass divergence failure mechanism in damping experiments with real 3D detonations exhibiting a strong transverse wave structure.

Experimental details

The experimental set-up consists of a 4 m long acrylic round tube, 50.8 mm in diameter. A schematic of the experimental set-up is shown in Fig. 1. The damping section is 45cm long with an inside diameter of 41mm. It consists of 14 layers of steel woven wire mesh tightly rolled together. Each layer has a hundred wires per inch, each wire having a 0.114-mm diameter. The porous "muffler" is perforated in 5mm intervals along one line in small 2mm holes, as to permit light detection inside the porous tube. Experiments are also conducted in a thin rectangular channel, 1m*10cm*4mm. It is separated into five porous wall mini-channels, 13 mm in height and 4 mm in width. Nine layers of attenuating mesh are placed on top and bottom of each mini-channel. The principal diagnostics for these experiments are streak and open shutter photography, which permit to measure the detonation attenuation process inside the damping section.

The mixtures investigated in this study are equimolar and stoichiometric acetylene-oxygen with different Argon dilutions, and stoichiometric methane-oxygen and propane-oxygen mixtures. The sensitivity of the mixtures is controlled by varying the initial pressure. The desired mixture composition is prepared before an experiment by the partial pressure technique in a separate mixing tank. The tube is evacuated before the premixed combustible gas is injected at the desired initial pressure. The mixture is ignited via a powerful electric spark by a capacitor bank discharge across a 3-mm spark gap situated at the end of the tube. The spark energy is approximately 1 J. An obstacle section is placed near the igniter to ensure the fast formation of a detonation wave.

Results and Discussion

Typical open shutter photographs of detonation damping in the flat channel are shown in Fig. 2. The equimolar acetylene-oxygen mixture is a typical example of a detonation exhibiting a strong transverse wave structure. One can see the highly luminous diamond shape patterns traced out by the combustion region behind the transverse waves. When the number of transverse waves across the channel is large (Fig. 2a), the detonation structure is only weakly affected by the damping walls. As the initial pressure is decreased and fewer transverse waves propagate across the channel's width, the "cells" enlarge in the damping section as the transverse waves are weakened (Fig. 2b). However, new cells can develop within the attenuated complex to maintain the self-sustained detonation. In this case, the rate of

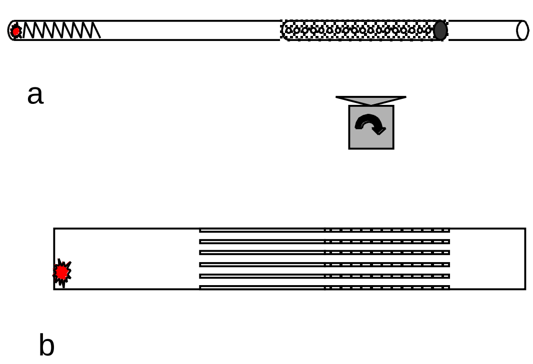

Fig. 1 Schematic of experimental setup in *a)* the circular tube, and *b)* the flat channel

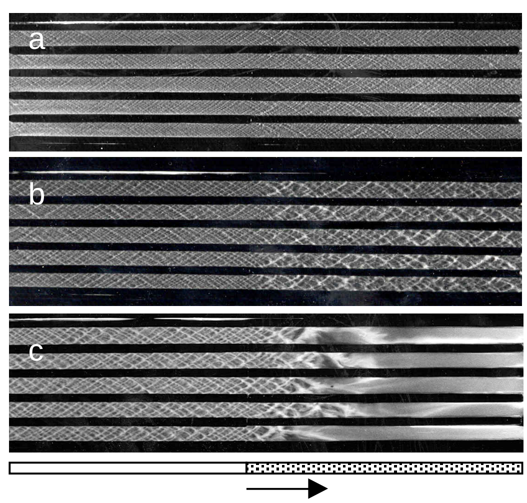

Fig. 2 Open shutter photographs of detonation damping in $C_2H_2 + O_2$ in the flat channel:
a) $P_O = 5$ kPa, *b)* $P_O = 3.8$ kPa, and *c)* $P_O = 2.5$ kPa

damping of transverse waves is less than the rate of new transverse wave generation and hence the detonation does not quench. When the rate of damping of transverse waves exceeds the rate in which new transverse waves can be generated, detonation fails (Fig 2c.). One can observe that in this case, the detonation fails very rapidly, after one or two transverse wave reflection form the porous wall.

In Fig. 3 are shown two typical streak records obtained at the critical damping conditions in round tubes. The two streak photographs illustrate, respectively, the attenuation and quenching of an unstable detonation in which transverse waves play a lead role (stoichiometric acetylene-oxygen), and of a stable quasi-ZND detonation relying mainly on the mechanism of gas ignition by shock compression alone (75% argon dilution). In the first case, one can clearly see the rapid and abrupt failure of the detonation wave as it enters in the damping section. Within approximately two tube diameters, the detonation wave abruptly fails. On the other hand, for high argon dilution, the nature of the attenuation process is fundamentally different. The detonation wave slowly decays in amplitude, then fails when it has reached a velocity deficit of approximately 20%. This failure mode is characteristic of detonations failing by the mass divergence mechanism (Lee, 1996). As the wave enters in the damping section, the wave is slowly influenced by the "leaking" boundary condition. The detonation pressure slowly decreases and the main shock gets progressively weaker until it reaches the point where auto-ignition becomes impossible.

The quantitative details of the detonation failure process in the unstable detonations can be seen in Fig. 4. The failure length L_F reported is the length between the point where the leading expansion fan reaches the porous tube axis and the point of complete disintegration of the detonation, as measured from the streak records. In this graph, the lengths to failure and tube diameter are normalized by the respective average transverse wave spacing λ. For the unstable mixtures, the critical damping occurs for $d / \lambda \approx 4$ for the three fuel-oxygen mixtures considered. Detonations in less sensitive mixtures, with fewer transverse waves across the tube, are damped in the porous section after a constant length of approximately 4 cell lengths. The conclusions that can be reached form the above results is that these unstable detonations require a minimum size kernel approximately 4 λ in diameter and 4 cells long to successfully overcome the attenuating effects of the damping tube. The measure of the critical damping diameter in unstable detonations thus provides an estimate of the hydrodynamic thickness of the wave Δ_H. These measurements agree with previous measurements reported by Edwards (1976) for the location of

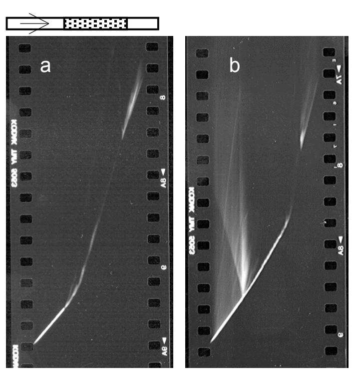

Fig. 3 Critical damping of detonations in round tubes:
a) $C_2H_2 + 2.5O_2$, P_O = 1.8kPa, d / λ 2.8, and
b) $C_2H_2 + 2.5\ O_2$ + 75%Ar, P_O = 24kPa, d / λ 10.2

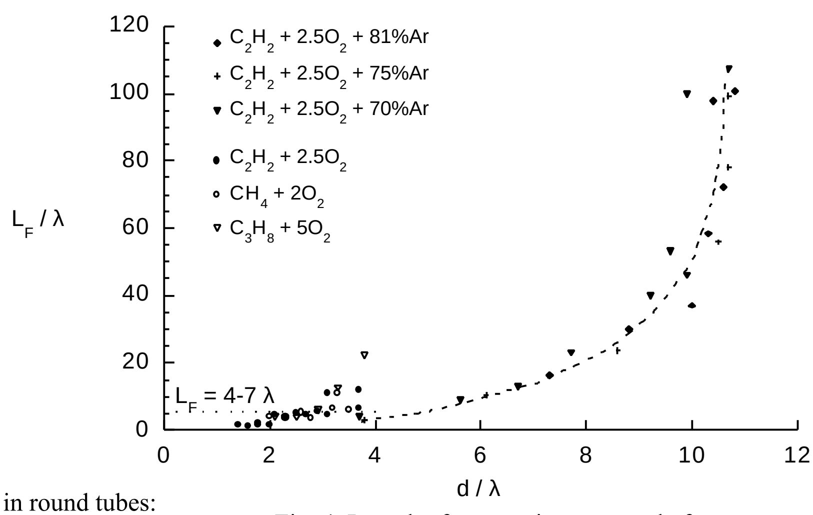

Fig. 4 Length of attenuation process before detonation failure in damping section

the effective CJ surface in acetylene-oxygen mixtures ($\Delta_H \approx 4$ cell lengths $\approx 6.5\ \lambda$).

However, for stable detonations, the results on failure length reported in Fig. 4 show a completely different trend, reflecting the change in the very propagation mechanisms of these detonations. For sake of comparison with the unstable detonations, the average cell width has been chosen as normalizing characteristic length scale of these detonations. For these stable argon-diluted mixtures, the length traveled by the detonation before failure is a strong monotonic function of mixture sensitivity (in the present experiments the tube diameter is constant). As the sensitivity of the mixture is increased (increasing d / λ), failure occurs further and further downstream. This slow damping, occurring on a length scale an order of magnitude larger than the length scale necessary to quench the unstable detonations, is typical of detonations failing by excess curvature alone. These results are similar to the results obtained for diffracting stable detonations from a round tube to an unconfined space, as discussed by Lee (1996). Upon emergence into the unconfined space, stable detonations fail due to global lateral gas expansions, resulting in curvature of the main front. Due to the slow increase in the frontal wave curvature, the time required for the failure wave to penetrate into the slowly curving front is much longer than the first expansion fan to reach the axis.

Further comparison between the failing length scales for the stable and unstable detonations presented in figure 4 also indicates the relative importance of mass divergence and weakening of the leading shock in unstable detonations. The two failing lengths for unstable and stable detonations obtained at criticality provide a measure of the length scale for transverse wave attenuation, and the length scale for leading shock attenuation due to mass divergence alone. At critical damping conditions, the stable mixtures fail on a length scale L_F an order of magnitude longer than the unstable mixtures. One can thus conclude that, for the unstable mixtures, detonation fails from transverse wave attenuation long before the attenuating effect from mass divergence begins to play a role. Equivalently, since the transverse wave attenuation is achieved in the unstable mixtures after one or two wall reflections (i.e. 1 – 2 tube diameters), the long attenuation process of the stable detonations (~10 tube diameters) indicates that the weak transverse wave system for these stable mixtures does not play any role in the propagation and failure mechanism.

The two different wave responses to the damping boundary conditions can also be observed

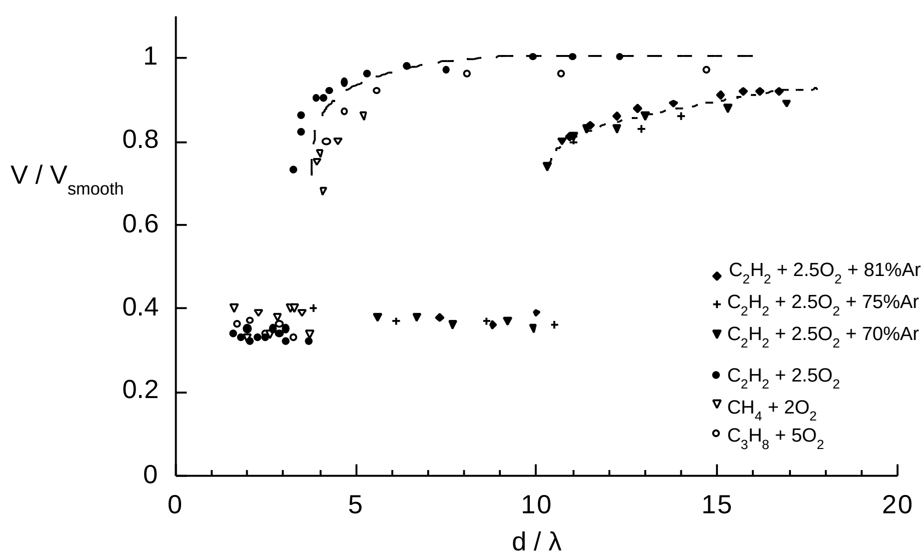

Fig. 5 Steady wave velocities inside the damping section

through the velocity deficit measurements shown in Fig. 5. These measurements represent the steady velocities of the damped detonations after relaxation to the new boundary conditions of the damping section. In all cases, the velocity of these damped waves is normalized by the detonation velocity measured in the smooth sections of the tube. For the unstable detonations (no argon dilution), the detonations exhibit only very small velocity deficits, until close to failure, when the rate of transverse wave attenuation is comparable to the rate of new transverse wave generation within the reaction zone. On the other hand, the highly diluted mixtures display progressively larger velocity deficits as the critical conditions for damping are approached, with critical velocity deficits of 20%. The strong velocity dependence on tube diameter, and therefore on the amount of mass divergence, is typical of ZND type detonations failing by mass divergence and excess wave curvature.

Concluding Remarks

In conclusion, for artificially stable detonations, the present results indicate that their weak transverse wave structure is irrelevant. These waves are quasi-ZND waves, which fail by the classical mechanism of mass divergence. On the other hand, for unstable detonations, the present results confirm the importance of their transverse waves. More importantly, the present study revealed that the maximum damping tube diameter necessary for damping may provide an estimate of the minimum detonation kernel size necessary for the self-propagation of detonations. This length scale, invariant in the various unstable mixtures studied, corresponds to the hydrodynamic thickness Δ_H, or the effective reaction zone thickness for these three-dimensional unstable detonations.

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