Large Scale Experiments on the Direct Initiation of Cylindrical Detonations

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Introduction

Unlike spherical detonations, direct initiation of cylindrical detonations is difficult to realize experimentally. Recently, Higgins *et al.* [1] investigated the direct initiation of quasi-cylindrical detonation using a high explosive detonating cord. The resulting flow fields are analogous to the problem of detonation initiation by a high velocity projectile. Although the energy release in the detonating cord is not instantaneous, the high velocity of detonation in the cord (~6 km/sec) permits the blast wave to be treated as a quasi-cylindrical blast wave by the hypersonic small disturbance theory. Although the results of Higgins *et al*. indicate that the direct initiation of cylindrical detonation can be investigated by this technique, their experiments were carried out in a relatively small cylindrical blast chamber (0.8 m by 0.5 m) which severely restricted the range of conditions that could be studied unambiguously. Furthermore, the chamber did not permit photographic observation of the initiation phenomenon. Measurements of the combustion front velocity as it propagated away from the detonating cord could only provide limited information about the critical regime of initiation. Thus, the motivation for the present study is to extend the range of mixture composition in order to provide a more comprehensive assessment of blast initiation theory, as applied to the cylindrical geometry. The present experiments are performed in large transparent plastic bags. This permits high-speed photographic observation of the initiation phenomenon, particularly of hot spot formation in the critical regime.

Experiment Overview

The large scale experiments were performed at the Defence Research Establishment Suffield (DRES), Alberta, Canada, in large 8-m-long, 2-m-diameter thin walled plastic bags. The experiments were conducted at ambient conditions (0.92 bar, 10-20 °C). Ethylene-air was used as the combustible mixture for all the tests. The mixtures were prepared by continuous re-circulation of the mixture inside the inflated bag. Fuel was injected periodically until the desired concentration was reached. The composition of the mixture was monitored by a "Wilks Miran 80" infrared analyzer via continuous sampling. This system guaranteed the mixture composition to within ±0.05% ethylene in air. After a uniform and stable mixture was obtained, the re-circulation fan was stopped before firing. A full description of the large scale facility at DRES had been provided previously by Funk and Murray.[2] The PETN cords used in the experiments had nominal core loadings of 50, 70, 200, and 400 gr./ft, yielding energies of 65, 91, 260, and 520 kJ/m. The detonating cord was kept taut by an elastic band to prevent sagging, and was initiated outside the bag by a Reynolds detonator (Fig. 1).

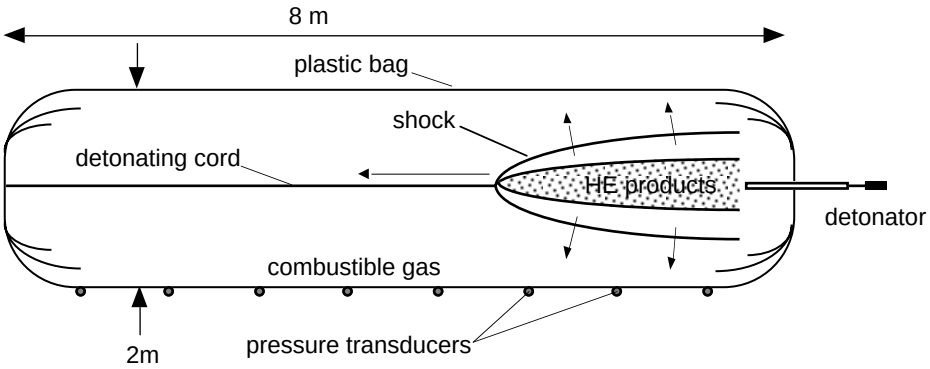

Fig. 1 Experiment Schematic

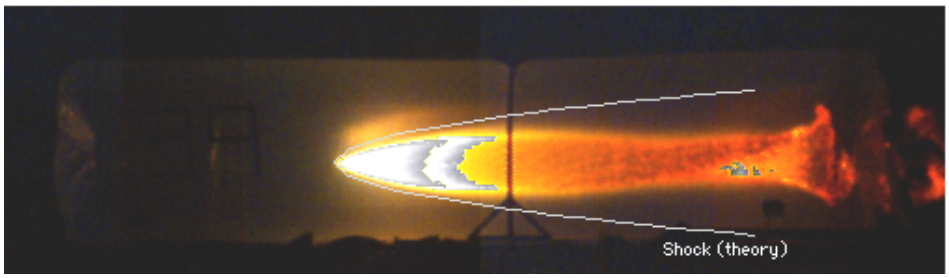

Fig. 2 Sub-critical regime: C_2H_4 – Air, E_S = 520 kJ/m, ϕ = 0.67

Fig. 3 Supercritical regime: C_2H_4 – Air, E_S = 65 kJ/m, ϕ = 1.07

For a given strength of cord, "go" or "no-go" conditions for direct initiation were determined by changing the sensitivity of the mixture via the fuel equivalence ratio. The result of an experiment was monitored by self-luminous high-speed video and cinematography with side-on and end-on views. Ionization probes attached on the PETN detonating cord measured its velocity. Pressure transducers mounted 1 meter apart along the pad floor provided a measure of the strength and time-of-arrival of the generated blast wave (or detonation).

Results and Discussion

As the detonation in the cord enters the bag, the expansion of the high explosive products drive a strong blast wave in the surrounding combustible gaseous mixture (Fig. 1). Chemical reactions are triggered by adiabatic shock compression. If the initial blast wave is too weak, the combustion fails to couple with the shock. In this "subcritical" regime of initiation, the unsupported shock decays, similar to a shock in air. The recorded time of arrival of the blast wave at the pressure transducers mounted along the pad floor for the subcritical experiments corresponded to the measured time of arrival of a blast in air. In the self-luminous high-speed photographs, only the highly luminous products of the detonating cord were observed (Fig. 2). Although not visible, the shape of the decaying shock can be inferred theoretically by using the blast wave analogy for hypersonic flows. For moderate shock strengths, the perturbation solution of Bach and Lee [3] for cylindrical blasts is adequate. The theoretical shock shape is shown superimposed on the image of a subcritical result (Fig. 2).

In the supercritical regime, when the energy released by the detonating cord is much greater than the critical energy of the mixture, the strong blast decays to a Chapman-Jouguet detonation. Since the detonation velocity in the gaseous mixture (~1.8 km/s) is less than the velocity of detonation in the cord (6 – 7 km/s), the gaseous detonation cannot overtake the detonation front in the cord. Instead, a conical detonation with half angle of ~17° is formed (Fig. 3), consistent with theory. This conical front translates along the length of the bag at the detonation velocity in the cord.

When the mixture composition becomes critical, more complex phenomena are observed. The blast wave does not decay continuously to a CJ detonation wave. Instead, initiation is governed by the appearance of explosion centers within the shocked gas layer. Spherical detonation "bubbles" develop from these localized centers in the appropriate chronological sequence to eventually coalesce and form an irregular conical detonation wave (Fig. 4). Near the limit of the critical regime, a small number of explosion centers may sometimes be observed to eventually develop into local self-sustained spherical detonations, as can be seen in Fig. 5a and 5b. From these two successive frames, it can be seen that the density of these explosion centers is insufficient to form a conical detonation. Instead, a highly asymmetrical front is formed. Eventually, after the detonation in the cord has exited the bag, the much slower spherical detonations encounter the bag boundary and transition to a planar detonation covering the entire cross section of the bag. The resulting planar detonation front propagates down the bag in pre-shocked gas at approximately 3 km/s (Fig. 5b).

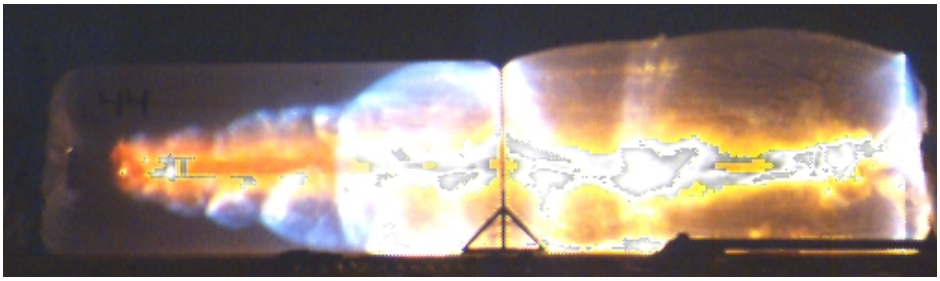

Fig. 4 Critical regime: C_2H_4 – Air, E_S = 65 kJ/m, ϕ = 1.03

a

b

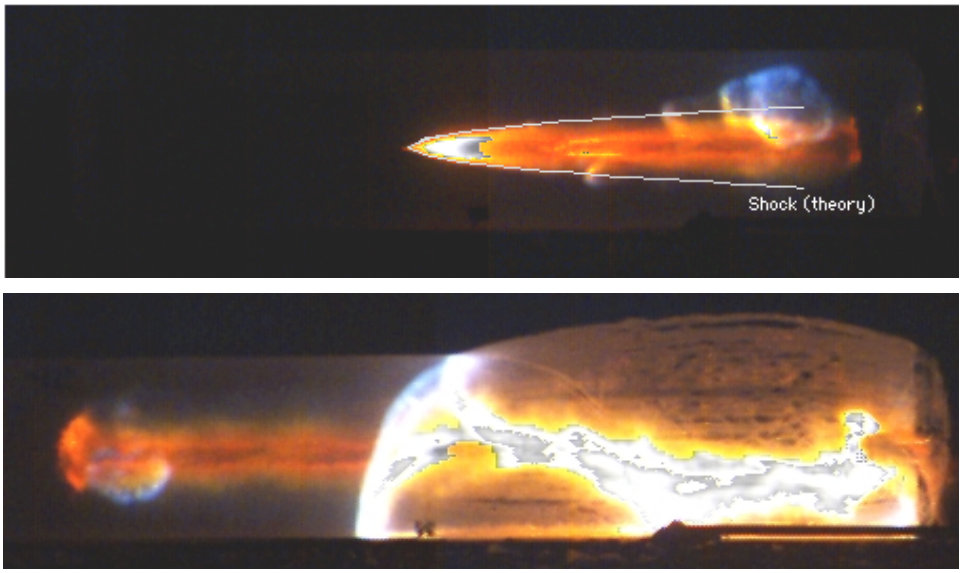

Fig. 5a and b Critical regime: C_2H_4 – Air, E_S = 65 kJ/m, ϕ = 0.98 (1 ms interval between frames)

The results of all the experiments are summarized in Fig. 6. Each experiment is categorized as "subcritical", "critical", or "supercritical" as described above. The experimentally determined critical conditions are compared with cylindrical initiation theory. The critical source energy required to directly initiate a detonation should be such that a blast wave above a critical strength (M_S*) is maintained over a critical distance of travel (R_S*). The critical Mach number is taken as the terminal velocity in a cell ($M_S^* \cong 0.6\, M_{CJ}$). The invariance of the explosion length for the different geometries ($R_O = (E_{cr}/P_O)^{1/j}$, j = 1, 2, 3 for planar, cylindrical and spherical) [4] requires that the critical radius R_S* to be scaled accordingly for each geometry. For the spherical geometry, the critical radius was shown to be about the hydrodynamic thickness of the detonation wave ($\Delta_H \cong 6.5\ \lambda$).[4] The corresponding critical radius in cylindrical initiation is thus found to be $R_S^* \cong 4.1\lambda$. The resulting functional relationship between critical energy and the cell width λ for a given mixture can be expressed as

$$E_{cr} = 23.9\gamma P_O M_{CJ}^2 \lambda^2 \qquad (1)$$

where γ is the specific heat ratio. Using the previously published cell size data for ethylene-air [5-8], the theoretical critical initiation energy is plotted in Fig. 6. The experimentally determined critical energies scale well with λ^2, which reflects initiation in the cylindrical geometry. The detonating cord technique appears suitable for the study of initiation of cylindrical detonations. Furthermore, the good agreement found between our experiments and cylindrical initiation theory clarifies the correct length scales that should be used in the initiation of a cylindrical detonation.

Concluding Remarks

The results of this study extend the previous work of Higgins *et al.* [1] on the direct initiation of quasi-cylindrical detonation by detonating cord. Good agreement with cylindrical theory of initiation is found. High-speed cinematography of the different flow fields confirms the stability of the oblique detonation in the supercritical regime, an important result for applications that seek to exploit oblique detonation for propulsion purposes (e.g., the ram accelerator). The critical regime is characterized by random localized spherical explosion

centers. This result shows that, like spherical initiation, the critical regime in cylindrical geometry is always associated with the formation of localized "hot spots". However, the appearances of these localized spherical detonations must have a sufficient density to merge and form a quasi-cylindrical detonation. Otherwise, the geometry of the resulting detonation is governed by the experimental boundary conditions. For the present case of a long plastic bag, the spherical detonation bubble grows to form a planar detonation spanning the cross-section of the bag.

Acknowledgements

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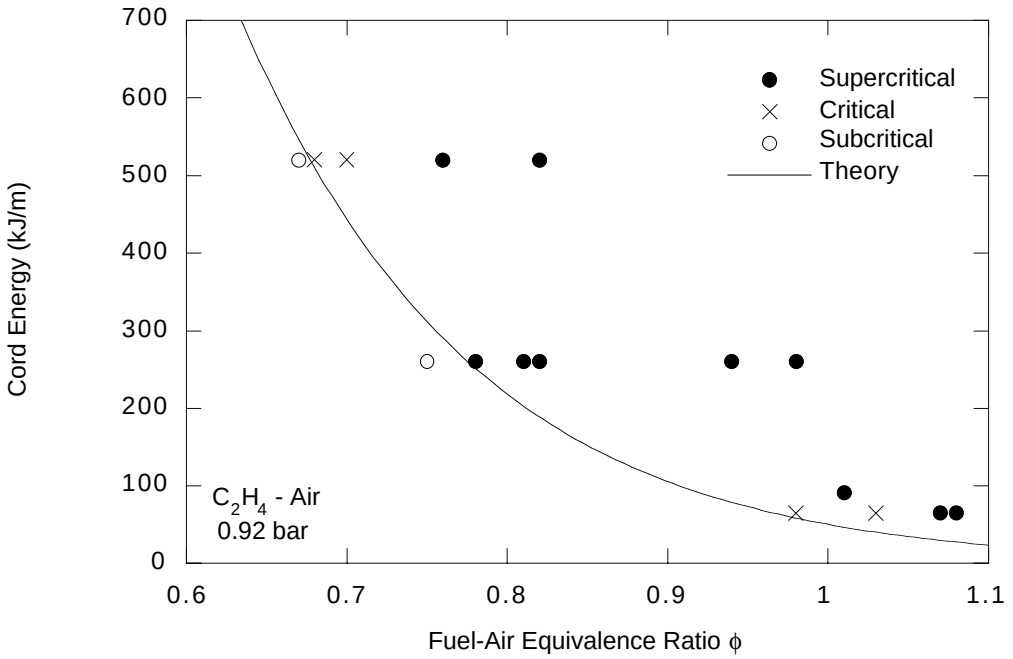

Fig. 6 Summary of results and comparison with cylindrical theory of initiation