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BRIEF COMMUNICATION

Transition to Detonation in a Large Fuel-Air Cloud

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1. INTRODUCTION

In assessing the blast hazards from fuel-air vapor cloud explosions, the possibility of transition from deflagration to detonation is of utmost concern. If such transition does occur, the resulting detonation will propagate throughout the cloud generating overpressures in excess of 15 atm. Most of the reported observations of transition from deflagration to detonation are for either sensitive fuel-oxygen mixtures or heavily confined configurations. The transition processes for hydrogen-oxygen mixtures in a confined tube have been revealed with unsurpassed clarity by the stroboscopic laser schlieren photographs of Urtiew and Oppenheim [1]. From these photographs it can be seen that the key feature associated with the onset of detonation is the formation of a localized explosion somewhere within the turbulent flame shock wave region.

Transitions from deflagration to detonation in fuel-air mixtures have also been observed in confined tubes [2-4]. In these cases the critical conditions for the onset of detonation are achieved by the acceleration of the flame to some critical speed. Whether sufficiently high flame speeds for transition by similar mechanisms can be achieved under less confined conditions has not been clarified. However, Lee et al. [5] and Knystautas et al. [6] have demonstrated in laboratory tests that strong shock waves associated with fast propagating flames in tubes or external high-energy sources are not required in order to create the conditions required for transition. The proposed transition mechanism is based on Shock Wave Amplification by Coherent Energy Release (SWACER), whereby the chemical energy in a local region is released in such a manner that the resulting shock waves are amplified to a strength sufficient to initiate detonation in the unburned gas. The SWACER mechanism and other mechanisms for transition from deflagration to detona-

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tion have been reviewed by Lee and Moen in Ref. [4]. All the proposed mechanisms require a high rate of energy release associated with fast burning or explosion of a sufficiently large volume in order for transition to occur. The rate of energy release and the minimum volume required depend on the sensitivity of the mixture to detonation. This sensitivity can be characterized by the detonation length scales (i.e., detonation cell size and critical tube diameter) and the critical initiation energy [7, 8]. Typically, the detonation length scales for fuel–air mixtures are at least an order of magnitude larger than those for fuel–oxygen, so that large scale tests are required in order to clarify the potential for transition to detonation in fuel–air mixtures.

The only reported transition observed in fuel–air mixtures without complete confinement is by Pförtner et al. [9]. They obtained transition to detonation by using a fan to generate turbulence in a hydrogen–air cloud (36% H_2, critical tube diameter ~ 0.2 m) contained in a 3 m × 3 m lane, 10 m long. Similar results, with jet ignition of smaller hydrogen–air clouds, have been obtained by Geiger and coworkers [10]. Transition to detonation in large semiconfined hydrogen–air clouds have also recently been reported by Fisk et al. [11].

The present paper describes the observation of transition to detonation in a lean acetylene–air cloud (critical tube diameter ~ 0.6 m) contained in a large plastic bag. The aim of the test series during which this transition was observed was not to investigate transition phenomena. However, the results from this one test were sufficiently revealing to warrant reporting separately.

2. EXPERIMENTAL DETAILS

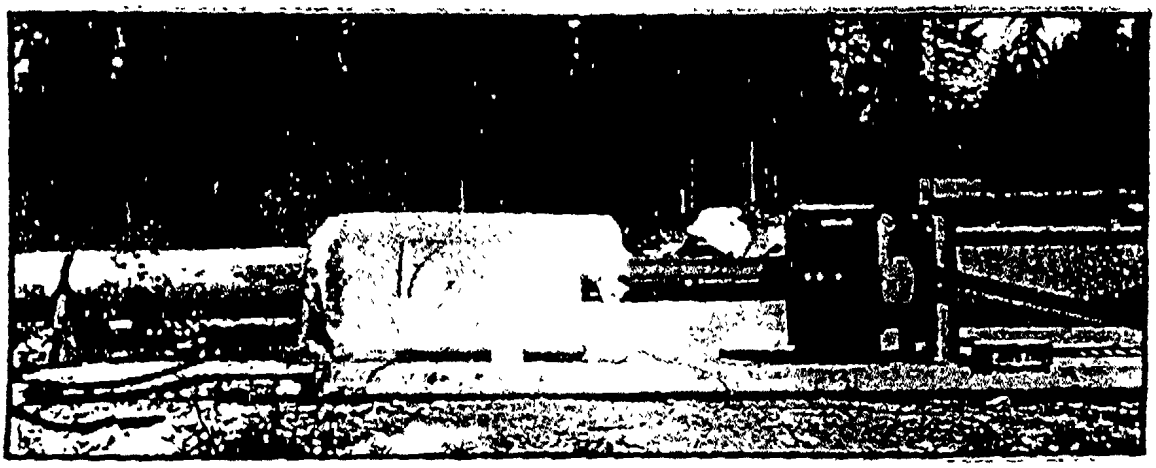
The test was performed at a large scale, fuel–air facility at Raufoss, Norway, as part of a test series to investigate the detonation properties of fuel–air mixtures. A sketch of the experimental configuration, which consists of three interconnected tubes of various diameters, is shown in Fig. 1. The final tube, which has a diameter of 0.63 m, is connected to a large plastic bag 2 m in diameter. The other end of the bag is connected to a camera shelter which blocks most of the bag cross section. The test gas (CP grade) was mixed with the initial air in the test section by a recirculation system and the composition and mixture homogeneity in the test volume were monitored by continuously analyzing samples at two ports in the test section using a "Wilks Miran 1A" infrared gas analyzer. In the present test the fuel concentration was determined to be 5% C_2H_2 in air, with an uncertainty of less than ± 0.05% fuel. The mixture in the tube assembly was ignited by a weak ignition source at the far end of the tube.

The diagnostic systems used in the test series included pressure transducers and two high-speed cameras. Unfortunately, the only diagnostic record available for the transition test discussed herein is the film from the high speed "Hycam" camera (10,000 half-frames/s) looking normal to the direction of propagation.

3. RESULTS AND DISCUSSION

Selected frames from the high speed photographic record of the flame propagation, transition to detonation, and detonation propagation are shown in Fig. 2. The trajectory of the flame and detonation fronts are plotted in Fig. 3.

By the time the flame emerges from the tube it has propagated from the open ignition end through the complex tube assembly shown in Fig. 1. In spite of the expansion and contractions in this assembly, transition to detonation does not occur. However, the flame speed is relatively high, reaching about 600 m/s as the flame emerges from the tube. The first frame in Fig. 2 shows the flame just as it emerges from the tube. The next frame shows the flame 2 ms later. By this time the main flame front in the center of the bag has slowed down to about 250 m/s. However, the flame is highly turbulent and unstable, with a tongue of flame running ahead at a speed of about 600 m/s near the bottom of the bag. This flame tongue reaches the lower corner at the end of the bag about 5.4 ms after the flame emerges from the tube. The resulting burning in this corner is seen in frames c and d



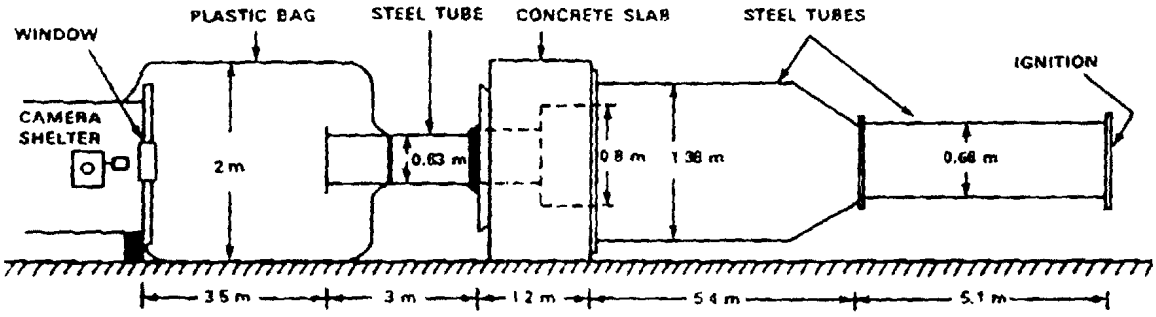


Fig. 1. Sketch of test configuration with photograph.

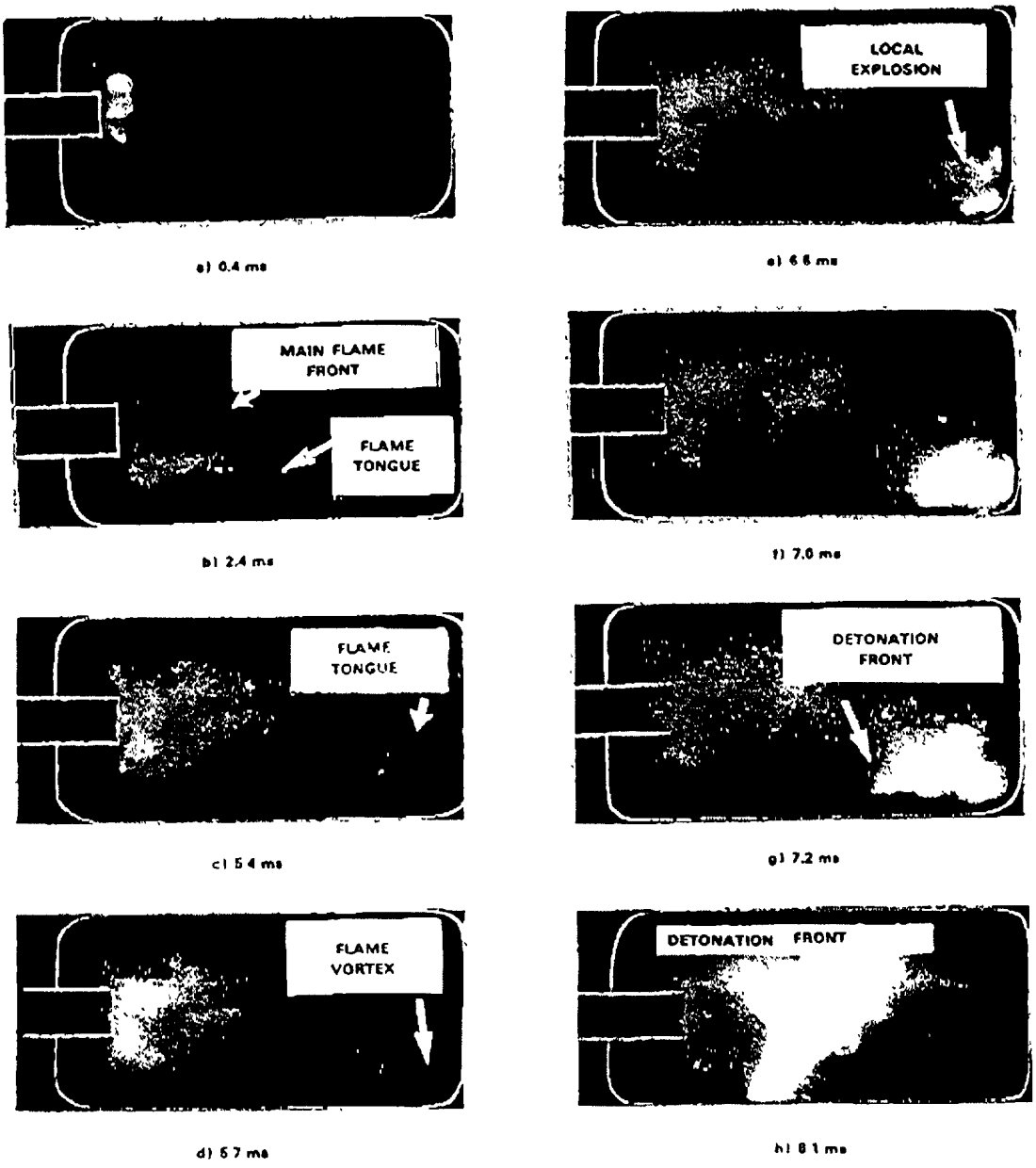


Fig. 2. Selected frames from high-speed movie showing flame propagation, explosion, and transition to detonation.

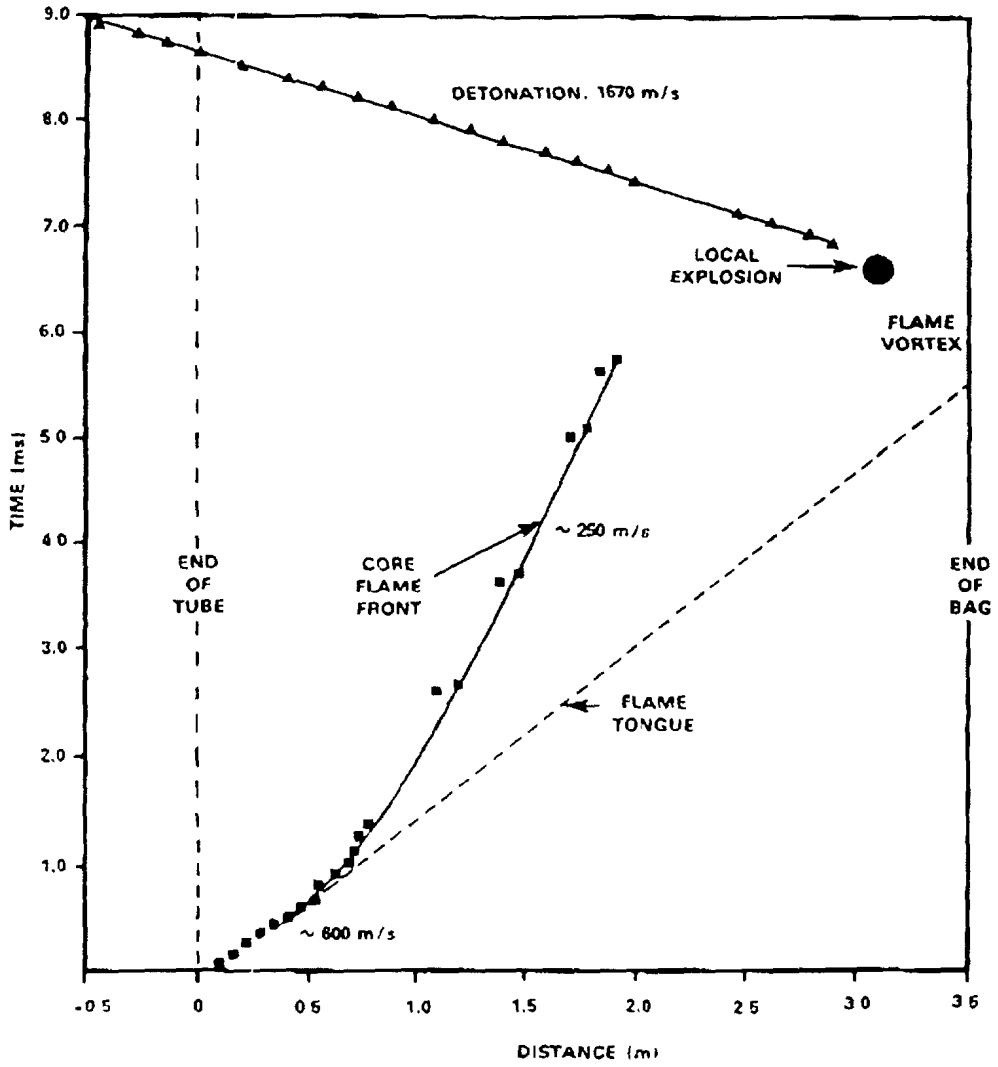


Fig. 3. Trajectories of flame and detonation fronts.

of Fig. 2. In frame d, a curled up flame vortex can be seen in the corner. The type of burning seen in these last two frames incubates for about 1.2 ms, at which time a localized explosion occurs in the corner (frame e). The subsequent growth of an explosion bubble into a detonation front propagating backward along the bottom of the bag can be seen in frames f and g. As seen in frame h, the resulting detonation wave engulfs the remaining unburned gas in the bag. It is important to note that the plastic bag remains intact until the detonation wave arrives so that there is no dilution of the mixture due to mixing with the outside air. The detonation wave therefore propagates at a speed of 1670 m/s, which is very close to the Chapman-Jouguet velocity of 1700 m/s for the 5% C_2H_2-air mixture in the bag.

The localized explosion, with the subsequent transition to detonation, is very similar to some of the observations of Urtiew and Oppenheim [1], but on a much larger scale with a less sensitive mixture. Unfortunately, the interaction of the flow ahead of the flame with the bag

boundaries, the ground and the solid surface at the end of the bag cannot be determined from the photographic records. However, it is clear that this flow is responsible for the highly turbulent and unstable flame propagation and the localized explosion leading to the onset of detonation. The relatively high flame speeds observed imply that shock waves are also present in the flow field ahead of the flame. In order to assess whether reflections of these shock waves could be responsible for the observed transition to detonation, two-dimensional numerical calculations of venting from the tube were performed using a finite-difference code with the flux-corrected transport (FCT) algorithm of Boris [12]. These calculations were not performed to model the flame propagation, but rather to obtain estimates of the pressures and temperatures expected in the flow, since no experimental pressure or temperature data were available. Several simplifying assumptions could therefore be made. The calculations were performed by prescribing a time-varying boundary condition at the end of the 0.63 m tube such that the motion of the unburned-burned gas interface coincided with the observed motion of the main-core flame. The flame tongue was not accounted for and no chemical reactions were included. The bag was assumed to be a solid perfectly reflecting surface in order to obtain upper bound estimates for the pressures and temperatures inside the bag.

Based on these calculations the incident pressure just prior to reflection off the end wall is $\Delta p/p_0 \simeq 0.3$ along the axis of the bag and 0.9 along the circumference. The maximum pressures computed after reflection are $\Delta p/p_0 = 4.65$ and 2.34, respectively. The relatively high incident pressure along the circumference is due to a previous reflection from the bag wall. It is in fact the implosion of this reflected wave which is partly responsible for the relatively high overpressure observed along the axis after reflection off the end wall. The maximum computed temperature in the corner of the bag is 430K, which is much too low to account for the observed explosion. It is therefore unlikely that transition to detonation is due solely to shock reflection. Rather, the effects of turbulent flame propagation, flame-shock interaction, and flame instabilities [4, 13] appear to have combined to produce the explosion responsible for the transition to detonation. No controlling mechanism can be discerned from the photographic records. However, the flame propagation is clearly highly turbulent and unstable, and the time of the explosion in the corner approximately coincides with the arrival of the computed reflected shock wave, indicating that all of the above mechanisms could have contributed to the explosion and subsequent transition to detonation.

4. CONCLUSION

Transition from deflagration to detonation has been observed in a lean acetylene–air cloud contained in a large plastic bag. This observation clearly demonstrates that transition phenomena, similar to those identified for more sensitive fuel–oxygen mixtures, can also occur in fuel–air mixtures, given a sufficiently large volume of explosive mixture. The observed transition from deflagration to detonation is in a relatively insensitive mixture of 5% acetylene in air, with a critical tube diameter of 0.6 m and a minimum detonation initiation energy corresponding to about 20 g of tetryl high-explosive. Both hydrogen and ethylene can produce fuel–air clouds which are more sensitive to detonation, and there is no reason to exclude similar transitions to detonation in less sensitive fuel–air mixtures. It is therefore important to quantify better the mechanism responsible for the observed transition to detonation, by performing better controlled and diagnosed tests supported by numerical simulations, so that potentially hazardous obstacle and confinement configurations associated with accidental spills of combustible fuels can be identified.

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