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Some observations on explosion development in process pipelines and implications for the selection and testing of explosion protection devices

G.O. Thomas

Aber Shock and Detonation Research Limited, c\o DDT Experts, PO Box 217, Aberystwyth SY23 3XT, UK

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ABSTRACT

In recent years there has been continuing interest in the potential hazards from detonations in pipelines. The interest has arisen in several instances due to the introduction of vapour recover systems, as part of measures to limit environmental emissions. These environmental pressures initially coincided with the preparation of new European-wide test procedures for explosion arrester devices and, more recently, moves to develop a new international ISO standard for the certification and approval of detonation arrester devices. It is an opportune time therefore to review current understanding of explosion development in pipelines and to consider the implications for plant design and explosion arrester selection and testing.

1. Introduction

Historically it has been widely accepted, with limited supporting evidence, that explosion events in pipelines, initiated by low energy sources ($E < 1$ J), first propagate as slow deflagrations. During this stage gas flow displacements ahead of the exothermic flame or reaction front are relatively small. The flame velocity relative to the pipe is also low (<300 ms^{-1}) so that the pressure increase ahead of the flame is less that 1 bar and no shock wave is formed.

As the flame front velocity increases, due to turbulent burning (deflagration) the overall explosion process may accelerate further. This is because of the positive feedback that arises following viscous interactions between unburnt gas ahead of the flame and the confining pipe walls. The resulting flow-induced turbulence and consequential increase in the turbulent mass burning rate in the trailing deflagration front complete the feedback loop feeding acoustic energy into the flow field ahead.

It is often cited, but not fully quantified, that further escalation of the explosion process can occur as the velocity of the shock–flame complex approaches ca. 1000 ms^{-1}. Localised explosions now develop, with significant transient overpressures in some cases. This is termed deflagration to detonation transition (or DDT). Immediately following this transition the detonation wave moves faster than that predicted from simple steady-state theory but is always decelerating and eventually reaches the steady or Chapman-Jouguet state. A true detonation will continue to propagate unsupported until the detonable mixture is exhausted. In the present paper recent but as yet unpublished results on deflagration to detonation transition are reviewed and implications for the testing and certification of detonation arrestors are discussed.

An example of a typical process pipeline explosion event is presented in Fig. 1, which shows time resolved pressure histories from a flame acceleration and eventual transition to detonation event in a 30 m long 150 mm diameter pipe. The mixture is 6.45% ethylene in air at ambient initial temperature and pressure. It is instructive to note that a significant fraction of the explosion event is associated with low velocity combustion.

Within the European Community the CEC ATEX directive, recently enforced, requires that all plant containing potentially explosive atmospheres should be adequately protected to prevent injury to personnel. For pipelines and detonation

E-mail address: geraint@abershock.com.

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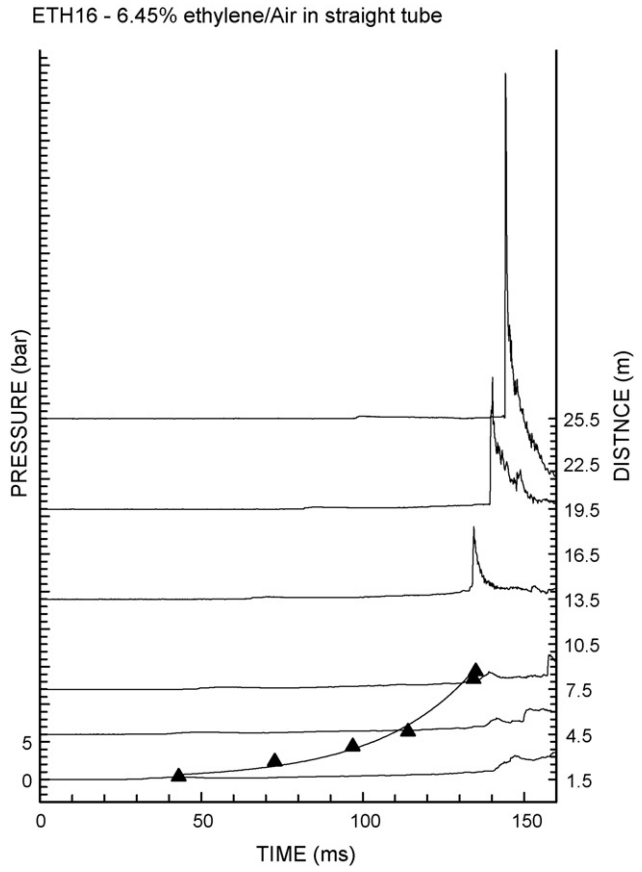

Fig. 1 – Plot of flame arrival time and pressure time histories at various gauge locations for a test with near stoichiometric ethylene–air showing a transition to detonation at ca. 17 m from the spark. Equivalence ratio: 1.02 ± 0.04.

arresters this requires installation of explosion arresters to isolate different sections of process plant. The results shown in Fig. 1 would suggest that, to protect comprehensively against pipe explosions, even if detonation is likely and potentially the most damaging phase, the other phases of explosion should also be considered. This is because there is no certainty that an arrester optimised for detonation will be equally as effective against lower velocity events and thus an incorrectly positioned arrester, optimised for detonation, could be capable of allowing a slower explosion event to propagate and evolve to a more severe event upstream of the arrester. Thus, for example, an incorrectly specified arrester installation might not always be effective in isolating a thermal oxidize from the main process even though the arrester might have been optimized for detonation. Similarly, an arrester optimised for low velocity deflagrations might not be effective when subjected to detonation loads.

2. Shock and detonation waves

2.1. *One-dimensional CJ detonations*

A shock wave is an abrupt gas dynamic discontinuity across which properties such as gas pressure, density, temperature and local flow velocities change discontinuously while mass, energy and momentum are conserved. One-dimensional detonation theory was developed independently by Chapman and Jouguet and was based on shock theory, with the inclusion of an addition energy term, Q, corresponding to the energy released by chemical reaction. In this theory, the CJ theory, the chemical reaction is assumed to occur infinitely fast and using the conservation equations for mass, energy and momentum it is possible to obtain Eq. (1) which relates the following.

The detonation wave Mach number M_{CJ}; the corresponding energy release q_{CJ}; the sound speed in the initial reactants (c_0); and the ratios of specific heats of the product gases γ_b

$$q_{CJ} = \frac{(M_{CJ}^2 - 1)^2 c_0^2}{2(\gamma_b - 1)M_{CJ}^2(\gamma_b + 1)} \quad (1)$$

CJ detonation theory assumes that reactants at initial pressure P_0, temperature T_0 and density ρ_0 are transformed instantaneously to products at a final pressure P_{CJ}, temperature T_{CJ} and density ρ_{CJ}.

Further, for CJ detonations curves can be drawn on the pressure-specific volume plane that link all possible final states, as shown schematically in Fig. 2. These are called Rankine–Hugoniot curves. The steady state solution is the point D_{CJ}, where a line drawn from the initial state, I, is tangent to the Rankine–Hugoniot curve. The absolute values of the final states (that is final pressure, velocity, etc.) also depend on the magnitude of the energy release and increasing the energy release gives a different steady state solution, e.g. at D^*. The velocity of a CJ detonation is, for all energy releases, directly related to the gradient of the line ID (the Rayleigh line) joining the initial state(I) and final state(D?) on the relevant Hugoniot.

Despite its relative simplicity CJ theory gives a remarkably accurate prediction of detonation velocities, D_{CJ} based only on knowledge of the initial physical and thermodynamic conditions, and despite the actual gasdynamic complexity of a real detonation.

A steady CJ detonation is one where the velocity and peak pressure are close to the theoretical CJ values. In addition, at a fixed measurement location, self-sustaining steady state detonations exhibit a typical pressure variation as a function of time, as illustrated in Fig. 3. In this figure the measured detonation peak pressure corresponds to the theoretical CJ pressure. The other striking characteristic is the form of the pressure falloff after the wave-front passes the pressure monitoring location, this expansion can be related to the

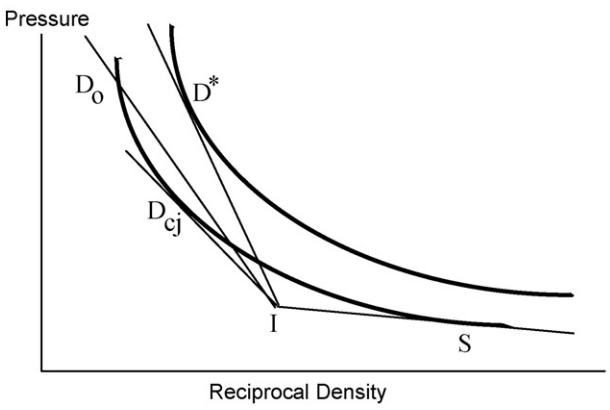

Fig. 2 – Sketch showing Rankine–Hugoniot curves for two different energy releases. Also marked are the steady-state CJ solution point D_{CJ} and an overdriven state D_0. D^* is the steady-state solution when the chemical energy release during the combustion reaction is increased.