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Deflagration to detonation transition in a vapour cloud explosion in open but congested space: Large scale test

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A R T I C L E I N F O

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A B S T R A C T

The paper reviews large scale experiments with various fuels in air where successful deflagration to detonation transition (DDT) took place. This includes a recent experiment disclosed in the Buncefield R&D program, where DDT developed in the propane/air mixture. The DDT occurred in branches of deciduous trees in a premixed stagnant mixture. An internal R&D investigation programme was initiated to better understand the phenomena. A large scale experiment in an open space with ethane air mixture is presented in the paper. The premixed mixture was ignited at the edge of the congested three-dimensional rigs which consisted of vertical and horizontal pipes. After ignition, the flame accelerated in the congestion and transitioned to detonation at the end of congestion. Stable detonation propagated through the remaining open and uncongested space.

The flame acceleration process leading to DDT is scale dependent. It also depends on many parameters leading to a large investigation array and, significant cost. However, such R&D efforts aimed toward a safer plant design, i.e. the prevention of occurrence of a major accident, are a small fraction of a real accident cost.

1. Introduction

Numerous experiments, from those at Maplin Sands (Hirst and Eyre, 1983) in 1980 onwards (Rodean et al., 1984), have shown that flames travelling through either premixed or non-premixed vapour clouds in unconfined and uncongested spaces do not accelerate significantly. The flame accelerates to a low steady state velocity; basically no significant overpressure is generated.

However, the presence of obstacles (such as pipes or vessels) in the path of the flame propagation will generate turbulence which can accelerate the flame to the velocities at which overpressure is generated. This process has been quantified in hundreds of experiments performed since the 1980s (Zeeuwen et al., 1983; Harris and Wickens, 1989). When a flame burns through an area congested by pipes and other obstacles, the flow driven by the flame generates turbulence. The resulting turbulent flame burns faster, more energy is released and expanding hot post combustion gases generate more turbulence through the subsequent obstacles, and so on. This positive feedback process is known as the Shchelkin mechanism. When flame acceleration continues to a high velocity a deflagration to detonation transition (DDT) may take place followed by a stable detonation. Such flame acceleration is one of the DDT mechanisms.

Flame acceleration in process plants is a complex phenomenon. The experimental evidence presented reveals that detonation may be induced during a flame acceleration process, given that certain critical requirements are met. In order to prevent detonative combustion, the need to better understand these necessary requirements led to systematic work on the DDT phenomena. In this paper we review relevant publications (describing large scale experiments and industrial accidents) and describe a large scale test with ethane air mixture.

2. Review of large scale experiments, and accidents leading to DDT

The accident at a fuel depot at Buncefield (2005) resulted in damage caused by a very high overpressure (Bradley et al., 2012). The congestion level of the pipework and other obstructions at the site was too low to generate such a high overpressure. However, the two lanes adjacent to the depot were bordered by wide verges containing trees and very dense undergrowth. This represented a high level of congestion. A visual inspection of the post accident site

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a few days after the accident suggested a very high probability of the flame acceleration mechanism occurring in these trees Private communication.

In the scenario of a complex layout of obstacles, when the flame velocity is sufficiently high, the flame acceleration generates pressure and shock waves ahead of the flame. This creates complex interactions between pressure waves and the flame front leading to a change in the combustion mechanism. The initial deflagrative combustion mechanism can transform into detonation in the deflagration to detonation transition. The process is scale dependent hence investigations in a small lab scale might not reveal all the phenomena.

Later, a numerical simulation of the accident confirmed this hypothesis. Simulations of the flame behaviour at Buncefield were reported in (Johnson et al., 2010; Buncefield Explosion Mechanism, 2009). These used EXSIM, one of a number of congested-plant explosion CFD models that have been developed and widely used over the last 20 years. The model has been validated against a range of experimental data obtained for simulating petrochemical plants. Applying it to trees and hedgerows is taking the model beyond its validation range. Thus, it could not have been used as a fully predictive tool for this sort of scenario until we have adequate data obtained from explosion experiments involving dense vegetation. However, it was possible to simulate the vegetation by arrays of pipe elements. The simulation that appears to match the conditions at Buncefield most closely included a representation of all scales of the congestion. This led to the acceleration of a deflagration flame speed to about 600 m/s in Three Cherry Trees Lane near to the junction with Buncefield Lane.

Another numerical simulation of the Buncefield accident was conducted using FLACS (Bakke et al., 2010). The result shows the same: flame acceleration along Three Cherry Trees Lane and generation of high overpressure. Additionally the authors experimentally investigated the effect of various bushes configuration on flame acceleration in a plastic-covered 20 m long tunnel that with a semicircular cross-section 3.2 m in diameter. Larger and more dense bushes generated higher flame velocity of maximum 63 m/s compared to flame speeds of 10–15 m/s observed for the empty tunnel.

A large-scale experimental study in a 3 m-square test rig up to 45 m long with a repetitive horizontal pipe obstacles by Harris and Wickens (1989) shows that cyclohexane air as well as propane air mixture undergoes DDT at the flame velocity of approximately 600 m/s. This value, however is not a constant value for the occurrence of the DDT process. A review of other large scale tests reveals a strong correlation between mixture reactivity and congestion level in the DDT process (Table 1).

Given the above reasons the Buncefield Explosion Mechanism Task Group concluded that the flame acceleration mechanism in the trees was the likely source for the overpressure generation (Buncefield Explosion Mechanism, 2009). A joint industry project

Fig. 1. A flame acceleration experiment in a 100 m long rig congested by pine trees. Deflagrative flame propagation is visible from right to left.

("Buncefield Phase 2" JIP) is focused on the role of congestion generated by trees and undergrowth with the intention to conduct large-scale field experiments in order to study some of the processes that may have been involved in the Buncefield explosion. Some of the experimental results have already been disclosed (New Scientist, 2012). A flame acceleration experiment was conducted in a 100 m long rig congested with pine trees with premixed propane air mixture (Fig. 1). After spark ignition the flame quickly accelerated to a certain value and propagated further with the attained, basically steady, state velocity. In a subsequent experiment the pine trees congestion was replaced by deciduous trees in a significantly shorter rig (Fig. 2). After ignition of the premixed propane air mixture the flame accelerated and deflagration to detonation transition occurred followed by a stable detonation. Such a result was anticipated however it was the first ever large scale experiment which demonstrated DDT in the presence of trees.

Highly computationally intensive simulation of the DDT process reveals additional features characteristic of DDT, i.e. a very short time scale as well as short length scale as compared to any computation of a deflagrative explosion. A numerical study of flame propagation in open, uncongested space but at high initial turbulence level showed a DDT occurrence for both the hydrogen air and methane air mixtures (Poludnenko et al., 2011).

The flame acceleration mechanism to DDT is one of the mechanisms leading to detonation; some others were briefly mentioned elsewhere (Puttock and Pekalski, 2011).

An accident in Jaipur, India (2009), with spilled gasoline also generated a very high overpressure. In addition, many overpressure

Table 1
DDT in fuel-air mixtures by flame acceleration in partly confined and congested configurations V_t – flame velocity at the transition, P_t-pressure just prior to the transition, e.r. – equivalence ratio.

Fuel, mole % in air	Configuration	V_t, (m/s)	P_t, (bar)	Ref
Hydrogen, 24.8%	30.5 m × 2.4 m x 1.8 m 13% Top venting	230	0.65	(Sherman et al., 1986)
Hydrogen, 36 & 38%	10 m × 3 m x 3 m Open-top lane with	220, 240	1.0	(Pfortner and Schneider, 1984)
Acetylene, near stoichiometric	15.5 m × 1.8 m x 1.8 m Obstacles ID 0.22 m	250	2.0	(Moen, 1993)
Acetylene, near stoichiometric	15.5 m × 1.8 m x 1.8 m Obstacles ID 0.5 m	400	–	(Moen, 1993)
Acetylene7.8%	15 m × 1.8 m x 1.8 m Open-top lane with obstacles	375, 435	>0.15	(Moen et al., 1986; Moen and Sulmistras, 1986)
Cyclohexane, 2.3%	45m × 3m × 3m Open-sided lane with obstacles	600	–	(Harris and Wickens, 1989)
Propane, 4.0%	45m × 3m × 3m Open-sided lane with obstacles	600	–	(Harris and Wickens, 1989)
Propane, 4.0%	10 m radial vessel with obstacles	500	–	(Bjorkhaug and Hjertager, 1986)
50:50 methane/hydrogen e.r. = 1.07	18m × 3m × 3m Open-sided lane with obstacles	750	3	(Lowesmith et al., 2011)