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Vapour cloud explosions in a long congested region involving methane/hydrogen mixtures

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ABSTRACT

A series of large scale vapour cloud explosions in a long congested region were conducted using methane/hydrogen mixtures. The congested region measured 3 m × 3 m × 18 m long and was preceded by a confined region which allowed an explosion flame with some initial flame speed and turbulence to be generated which then entered the congested region. During the experiments the flame speed and explosion overpressure were measured through the congested region. The hydrogen content in the methane/hydrogen mixture was varied from 0 to 50% by volume. A key objective was to determine factors that could lead to continued flame acceleration through the congested region, such as the hydrogen concentration, the initial flame speed entering the congestion and the level of congestion. The results are reported together with some detailed observations of the complex nature of pressure traces produced by explosion events of this type.

Keywords: Vapour cloud explosions; Methane/hydrogen mixtures; VCE; Large scale experimental data

1. Background

Hydrogen is seen as an important energy carrier for the future which offers carbon free emissions at the point of use. However, transition to the hydrogen economy is likely to be lengthy and will take considerable investment with major changes to the technologies required for the manufacture, transport and use of hydrogen. In order to facilitate the transition to the hydrogen economy, the EC-funded project Naturalhy (NATURALHY, 2010) has studied the potential for the existing natural gas pipeline networks to transport hydrogen from manufacturing sites to hydrogen users. The hydrogen, introduced into the pipeline network, would mix with the natural gas. The end-user may then extract the hydrogen for use in fuel cell applications or burn the gas mixture directly within existing gas-fired appliances, thereby reducing carbon emissions compared to natural gas. Using the existing pipeline network to convey hydrogen in this way would enable hydrogen production and hydrogen fuelled applications to become established prior to the development of a dedicated hydrogen transportation system, which would require considerable capital investment and time for construction.

However, the existing gas pipeline networks are designed, constructed and operated based on the premise that natural gas is the material to be conveyed. Hydrogen has different chemical and physical properties which may adversely affect the integrity or durability of the pipeline network, or which may increase the risk presented to the public. For these reasons, the Naturalhy project (www.naturalhy.net) has assessed the feasibility and impact of introducing hydrogen into a natural gas pipeline system. Determining any change in risk to the public was a major part of this project. As part of the safety related work, the consequences of explosions following a release of methane/hydrogen have been considered, both for confined vented explosions (Lowesmith et al., 2010) and for vapour cloud explosions (VCEs) in unconfined congested regions (Royle et al., 2007), including that reported here.

2. Introduction

It has been long understood that gas/air explosions can generate significant overpressure, even without the presence of confining walls, especially when the gas cloud encompasses a region of obstacles (congestion). In these cases, high flame

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speeds can be produced, generating damaging overpressures. In some extreme circumstances, a transition from deflagration to detonation (DDT) can occur. Detonations are self-sustaining as long as the concentration of the gas is within certain limits. In a detonation, the flame front and shock wave are coupled and travel at a speed of approximately 2000 m s^{-1} and very high overpressures (in the region of 20 bar or more) result. In the context of the gas industry, the possibility of a detonation occurring on a gas processing installation is a serious concern as the region in which high overpressures are generated extends beyond that of the congestion and hence possibly beyond the boundary of the site and so presents a greater hazard to the surrounding population.

Previous studies of vapour cloud explosions in unconfined congested regions have shown that more reactive fuels (with higher laminar burning velocities such as propane or ethylene as compared to methane) are more susceptible to flame acceleration through the congestion. The level of congestion (area blockage) and the size of the obstacles also have an effect (MERGE, 1994; Snowden, 1999; Harris and Wickens, 1989), with increased blockage and smaller obstacles giving rise to increased overpressure.

Project MERGE involved experiments at small, medium and large scale with methane, propane and ethylene fuels (MERGE, 1994). The congested regions were formed by regular three dimensional grids of pipework measuring, in the large scale experiments, 9 m square and 4.5 m high. The medium and small scale experiments were conducted with congested regions one half and one quarter of the large scale region respectively. Only methane and propane fuels were used at large scale. In the propane experiments, shock waves were measured as the flame exited from the congested region that suggested that localised transition to detonation had occurred. However, as the gas cloud was limited to the congested region, it was not possible to confirm sustained propagation of the detonation. Shock waves of this type were not observed in the methane experiments.

In work reported by Snowden (1999), in a compact congested region measuring 3 m × 3 m × 2 m and ignited centrally, increased pressure was observed for ethylene compared to propane and propane compared to methane but no detonations were observed. However, hydrogen is well known for its susceptibility to detonate. Using the same test facility, Royle et al. (2007) showed that a hydrogen/air mixture, can result in DDT, but detonation was not observed with methane:hydrogen ratios up to 25:75 (by volume). However, the path length through the congestion from the point of ignition (and hence time for flame acceleration) was relatively short during these experiments.

A key difference in the behaviour of natural gas (predominantly methane), compared to higher hydrocarbons such as propane, was observed in experiments using a congested region up to 45 m long (Harris and Wickens, 1989). Whilst flame acceleration occurred for all the fuels, in the case of natural gas the flame speed reached a plateau and there was no evidence of the potential for DDT with natural gas. By contrast, with the more reactive higher hydrocarbons, continued flame acceleration could be produced within long congested regions and with propane and cyclohexane, resulted in a DDT, generating very high damaging overpressures, even in unobstructed regions of the cloud.

The importance of understanding the potential for generating high flame speeds and DDT was illustrated by the Buncefield incident in December 2005 (HSE, 2009). This incident involved the spillage of 300 Tonnes of gasoline at a storage site, generating a vapour cloud that covered approximately 120,000 m^2 with an estimated depth of 2 m. Ignition resulted in a vapour cloud explosion that caused considerable overpressure damage and led to major tank fires that burned for several days. Investigation of the explosion mechanism concluded that the most likely explanation was acceleration of a flame in a line of trees that then led to a DDT, with the detonation then propagating through most of the flammable cloud, including offsite areas.

The key question addressed here is; how much hydrogen can be added to natural gas, before the risk of high speed explosion flames and potential DDT becomes significant? The experimental programme reported here was designed to address this question, by varying the hydrogen content in the fuel and the initial flame speed entering the congested region. This was achieved by having an initial confined region (chamber) that vented a flame into an external congested region. The speed of the flame venting from the confined region could be varied by varying the degree of congestion inside the chamber and ignition location. To some extent, the situation also represents what would happen if ignition occurred in a much longer congested region.

In this work, a series of large scale vapour cloud explosions experiments were performed with methane and methane:hydrogen mixtures up to 50:50 (by volume). The experiments were performed at the GL Noble Denton Spadeadam Test Site in Cumbria, UK on behalf of Loughborough University as part of the NATURALHY Project.

3. Experimental arrangement

The test rig (Fig. 1) comprised a long congested region measuring 3 m × 3 m × 18 m long following an enclosure (or chamber)

Fig. 1 – The test rig with congested region covered in polythene prior to gas filling.