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Ignited releases of liquid hydrogen: Safety considerations of thermal and overpressure effects

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ABSTRACT

If the 'Hydrogen Economy' is to progress, more hydrogen fuelling stations are required. In the short term and in the absence of a hydrogen distribution network, these fuelling stations will have to be supplied by liquid hydrogen (LH2) road tankers. Such a development will increase the number of tanker offloading operations significantly and these may need to be performed in close proximity to the general public.

The aim of this work was to determine the hazards and severity of a realistic ignited spill of LH2 focussing on; flammability limits of an LH2 vapour cloud, flame speeds through an LH2 vapour cloud and subsequent radiative heat levels after ignition. The experimental findings presented are split into three phenomena; jet-fires in high and low wind conditions, 'burn-back' of ignited clouds and secondary explosions7 post 'burn-back'. An attempt was made to estimate the magnitude of an explosion that occurred during one of the releases. The resulting data were used to propose safety distances for LH2 offloading facilities which will help to update and develop guidance for codes and standards.

Introduction

The 'Hydrogen Economy' is gathering pace internationally and now in the UK. Over the last year a number of vehicle related demonstration projects have appeared, linked to the 2012 Olympics. Whilst in the long term, the key to the development of a hydrogen economy is a full infrastructure to support it, a short bridging option for hydrogen refuelling stations particularly, is the bulk storage and transport of cryogenic hydrogen, referred to in industry as LH2. Although cryogenic liquid storage has been used safely for many years in secure and regulated industrial sites, its use in relatively congested highly populated urban areas presents a new set of problems in relation to security, safety and associated planning. There is previous work undertaken by NASA on LH2 relating to its spill behaviour [1], but this was performed in a low humidity desert environment.

Research is therefore needed to identify and address issues relating to bulk LH2 storage facilities associated with hydrogen refuelling stations located in urban environments so that further guidance on their safe management can be developed.

Issues in particular relating to LH2 include: flame speed, ignition behaviour as a cool/dense vapour and the complications of this associated with layering effects, LH2's low boiling point and associated ability to condense out and even solidify oxygen from air to produce a potentially hypergolic mixture of LH2 and liquid or solid oxygen.

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Un-ignited releases

During 2009–2011 Royle and Willoughby performed experiments on large-scale un-ignited releases of LH2 [2] with the aim of determining the range of hazards from a realistic release of LH2.

The work involved releasing LH2 at fixed conditions of 1 barg in the tanker through 20 m of 1" n.b. hose, which gave a rate of 60 L per minute for differing durations. The release height and orientation were varied and the sensor positions were changed.

Aims of investigation into ignited releases

This series of experiments followed on from the un-ignited experimental results (summarised above) to establish the severity of an ignition from a release of LH2 with comparable spill rates, consistent with a transfer hose operation.

A number of distinct areas relating to an ignition were investigated: flammable extent of a vapour cloud; flame speeds through a vapour cloud; radiative heat levels generated during ignition.

Experimental set up

The facility was situated at the Frith Valley site at the Health and Safety Laboratory in Buxton.

Release facility

The LH2 release system comprised the 2.5 tonne capacity LH2 tanker, 20 m of 1" n.b. vacuum insulated hose, a release valve station with bypass purge and release valves, an LH2 bypass hose and a 6 m high vent stack to vent excess hydrogen.

On receipt of delivery, the hydrogen within the tanker was normally at around 4 bar pressure and as such it was superheated relative to its atmospheric boiling point of 20 K. In order to achieve a liquid spill of the contents at atmospheric pressure without excessive flash vaporisation, the tanker was first depressurised to atmospheric pressure by venting hydrogen from the vapour space above the liquid, thereby cooling the remaining LH2 within the tanker to its atmospheric boiling point. Some LH2 was then allowed to flow into the hydrogen/air heat exchanger where it vaporised repressurised the LH2 such that it would flow out of the tanker at a nominal flow rate (60 l/min).

Additionally for these ignited trials, a metal shield 1.26 m $\times$ 1.6 m was fitted to protect the release point from fire or overpressure damage.

Instrumentation

During the tests the following measurements were made: flammable extent and flame speed; radiative heat (six fast response ellipsoidal radiometers); meteorological measurement. To ignite the hydrogen vapour cloud 1 kJ Sobbe chemical igniters were used at four positions on the test pad. The optimum positions for the igniters were established using concentration data taken from previous un-ignited tests.

Results

Fourteen tests were performed in total, of which four were non-ignitions. The reason for the non-ignitions is not clear; it may be that the gas cloud was under or over-rich in hydrogen at the point that the igniters were fired due to differing dispersion and wind effects, or a quenching effect was created by the water vapour created by the cold hydrogen cloud.

During the test programme the ignition delay was varied between ~60 and ~320 s. The longer tests allowed for a larger build-up of flammable cloud and also reproduced the liquid/solid pooling phenomena first seen during un-ignited releases of LH2 [2]. The extent of the flammable cloud appeared to be congruent with the visible extent of the water vapour cloud created by the very cold hydrogen cloud when IR footage was compared with visible footage. The flame speeds were measured for each test from the high-speed video and found to develop from 25 m/s up to 50 m/s with increasing release duration.

On one occasion, as the cloud was ignited; it burnt back to source creating a jet-fire and then a secondary explosion appeared to emanate from the liquid/solid pool location. The separate phases of the burning cloud are highlighted in the radiometer plot from the test, shown Fig. 1. The first peak on the plot represents the initial deflagration of the cloud back to the release point or 'burn-back'; the second larger peak represents the secondary explosion and the longer radiative phase after represents the resulting jet-fire. The varying plot levels correspond to the six radiometers located at increasing distances from the release point.

Secondary explosion

The secondary explosion occurred close to the release point after the LH2 had been released at ground level, during windy conditions, for 258 s without significant pre-cooling of the concrete. The explosion occurred after the hydrogen cloud had been ignited, burned back to the release point and then burned steadily for 3.6 s. From IR video footage, the explosion was estimated to be of a hemispherical profile and approximately 8 m in diameter, emanating 2.5 m from the release point, corresponding with the location of the solid/liquid pool seen prior to ignition.

Several attempts were made to reproduce this phenomenon without success, although the conditions on subsequent occasions were far less windy, with the wind in the opposite direction. It is possible that oxygen enrichment of the condensed air may have occurred due to oxygen's higher boiling temperature (90.19 K) than nitrogen (77.36 K), an effect that may have been more likely during the windy conditions. It is postulated that the explosion was either a gas phase explosion resulting from a sudden release of oxygen from the solid due to a rapid phase change, or even a rapid reaction within the condensed slurry of solidified air and LH2 if the oxygen concentration were high enough [1]. Unfortunately, at the time of the explosion no pressure measurements were being made. Therefore, it was necessary to estimate the "size" of the explosion by other means.