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Effects of congestion and confining walls on turbulent deflagrations in a hydrogen storage facility-part 1: Experimental study

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ABSTRACT

If the general public is to use hydrogen as a vehicle fuel, customers must be able to handle hydrogen with the same degree of confidence, and with comparable risk, as conventional liquid and gaseous fuels. Since hydrogen is stored and used as a high-pressure gas, a jet release in a confined or congested area can create an explosion hazard. Therefore, hazards associated with jet releases from leaks in a vehicle-refuelling environment must be considered. As there was insufficient knowledge of the explosion hazards, a study was initiated to gain a better understanding of the potential explosion hazard consequences associated with high-pressure leaks from hydrogen vehicle refuelling systems. Our first paper [1] describes the release and subsequent ignition of a high-pressure hydrogen jet in a simulated dispensing area of a hydrogen vehicle refuelling station. In the present paper, an array of dummy storage cylinders with confining walls (to represent isolation from the forecourt area) was used to represent high-pressure hydrogen cylinder storage congestion. Experiments with ignition of premixed 5.4 m × 6.0 m × 2.5 m hydrogen-air clouds and hydrogen jet releases up to 40 MPa pressures were performed. The results are presented and discussed in relation to the conditions giving the highest overpressures. We concluded from the study that the ignition of a jet release gives much higher local overpressure than in the case of ignition of a homogeneous mixture inside the cylinder storage congestion area. The modelling of these results will be presented in Part 2 of this paper.

Introduction

For the safe design of hydrogen vehicle refuelling facilities, it is essential to understand the hazards that could arise following an accidental release of hydrogen. Furthermore, it is essential to have experimental data to allow the appropriate codes and standards to be developed. If hydrogen is stored and used as a high-pressure gas, the hazards associated with jet releases must also be considered.

A jet release in an open area will result in a flammable cloud. If this finds an ignition source, the result will be a cloud

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fire that burns back leaving a jet fire burning from the leak, until the supply is controlled or exhausted. If, however the jet release is into a confined or congested area an explosion may occur if the cloud is ignited. Depending on the type and degree of confinement or congestion, the explosion may result in an overpressure damaging to both equipment and people.

An industry funded hydrogen safety study was initiated to investigate explosion hazards posed by high-pressure hydrogen leaks in a vehicle refuelling environment. The overall objective of this study was to gain a better understanding of the potential explosion hazard consequences associated with high-pressure leaks from hydrogen vehicle refuelling systems.

The study was conducted in three parts. In the first part, a series of experiments were designed to establish hydrogen–air explosion overpressures in a well-defined, and well understood, repeated pipe congestion geometry. More realistic environments were chosen for the second and third parts; one was a stack of dummy storage cylinders to represent the high-pressure hydrogen storage and the other comprised of a dummy vehicle and dispenser units (Refuelling Station Congestion). An overview of all three parts of the work performed is given by Shirvill and Roberts [2].

The experimental study describing high-pressure hydrogen releases ignited in a simulated dispensing area of a hydrogen vehicle refuelling station was presented in our previous paper [1]. These results have since been used by others to test Computational Fluid Dynamics (CFD) based explosion models [3,4]. Until now the results from the releases ignited in the simulated hydrogen cylinder storage area (second part of the study) have only been available to our collaborators in the International Energy Agency (IEA) Annex 19 on Hydrogen Safety [5]. The authors now wish to make these results more widely available for others to validate their explosion models. Validated explosion models are essential to quantify the consequences of ignited releases in the many different configurations to be found in emerging hydrogen vehicle refuelling stations. The experimental results are presented in this paper (Part-1). We have presented numerical modelling of these experiments in Part 2 of this paper [6].

It should be noted that in this paper, we consider only the consequences of a leak, subsequent ignition and the resultant explosion. We do not address the likelihood of these events, and thus the risks, beyond observing that in a well-engineered and safeguarded system the probability of such events occurring should be very low. Others have attempted to quantify the risks posed by hydrogen stations using quantitative risk Assessment (QRA) techniques [7–15]. Methods based on CFD (see for example Kikukawa [16], Baraldi et al. [17] and Venetsanos et al. [18]) were also used to investigate safety analysis of hydrogen fuelling stations. All these methods are limited by the paucity of reliable data on leak frequencies specific to high-pressure hydrogen systems. It will take many hydrogen stations operating for many years before these data improve. At present, only generic data from the oil and gas industries can be used. LaChance et al. [19] and Haugom et al. [20] have shown how sophisticated Bayesian analysis techniques can be utilized to refine the available generic data. Furthermore, they have developed risk-informed separation distances for hydrogen codes and standards.

Typically, an optimally flammable cloud is considered as the “worst-case” scenario when assessing consequences from an explosion hazard. If the extent of the gas cloud is far beyond the congested region, it will not greatly increase the severity of the event as the flame speed will reduce once flame leaves the congestion. This is only true for a deflagrating flame. However, in the case of deflagration to detonation transition (DDT), any uncongested extended cloud may also detonate if the mixture is within the detonable range (18.3%–59% by volume for hydrogen). This ‘worst-case’ scenario is the least challenging for explosion modelling but may not in fact represent the most onerous condition because the flammable mixture is taken to be in a quiescent state. A more credible scenario is that of a representative ‘realistic’ jet release scenario. In this case, hydrogen will be released initially at the system pressure and the pressure will then reduce as the inventory is depleted or limited by safeguarding isolations. This release will produce high initial turbulence which will reduce as the pressure drops if there is no immediate ignition. It is possible that the overpressures resulting from the higher initial turbulence may be greater than the overpressures generated by a larger cloud with lower turbulence, especially as this cloud will not be optimally mixed.

The philosophy behind the design of our refuelling station experiments (also used in Ref. [1]) was to reproduce the main components of a refuelling station in a simplified and robust form. These components were then enveloped in homogeneous hydrogen-air clouds to determine the ‘worst-case ‘deflagration overpressures. The concentration of the mixture was chosen such that it generates the highest overpressure. Similarly, the ignition locations expected to result in the highest overpressures was selected based on experience. The size and location of the releases were chosen to represent realistic leak scenarios for the jet release experiments. They were of short duration and from small-bore piping (8 mm) at system pressures up to 40 MPa. Pressures above 70 MPa are to be found on some current hydrogen refuelling stations but at the time of these experiments no facilities were readily available at pressures above 40 MPa. The release durations were contrived to discharge quantities of hydrogen that bracketed the amount used in the premixed experiments.

The Health and Safety Laboratory (HSL), Buxton, carried out the premixed experiments presented in this paper. The jet release experiments were contracted to Advantica Spadeadam (now DNV GL Spadeadam) to benefit from their extant capability to deliver hydrogen at pressures up to 40 MPa.

The paper is structured as follows: Firstly, Section Cylinder storage congestion describes the cylinder storage congestion experimental rig. Secondly, Section Types of experiment describes two different types of experiments performed in this study. Thirdly, Section Pre-mixed hydrogen-air experiments and Jet release hydrogen-air experiment describes the premixed hydrogen-air experiments and jet release experiments. Fourthly, Section Comparison of premixed hydrogen–air and jet-release experiments compares the results from the premixed hydrogen-air and jet release experiments. Fifthly, Section Pressure and radiation effects describes the pressure and radiation effects. While, Section Comparison of experimental results with similar studies compares the present experimental results with other similar studies

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