SAFE HYDROGEN FUEL HANDLING AND USE FOR EFFICIENT IMPLEMENTATION – SH_2IFT

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ABSTRACT

The SH_2IFT project combines social and technical scientific methods to address knowledge gaps regarding safe handling and use of gaseous and liquid hydrogen. Theoretical approaches will be complemented by fire and explosion experiments, with emphasis on topics of strategic importance to Norway, such as tunnel safety, maritime applications, etc. Experiments include Rapid Phase Transition, Boiling Liquid Expanding Vapour Explosion and jet fires. This paper gives an overview of the project and preliminary results.

1.0 BACKGROUND

There is an increased interest in hydrogen as a zero - or low-carbon fuel that can contribute to realize the needed global reductions in greenhouse gas emission. In particular, decarbonization of large scale applications such as power and industry, as well as several modes of transportation are of high interest. Further, hydrogen is highly attractive as a storage medium for intermittent, renewable energy. Norway has extensive experience from hydrogen producing by electrolysis and methane reforming, and can become a supplier of clean hydrogen and hydrogen technology to Europe and other parts of the world.

However, insufficient knowledge about safety issues related to widespread roll-out of hydrogen technology represents a major bottleneck for industry, authorities, end-users and the general public. To avoid unnecessary restrictions regarding handling and use of hydrogen, knowledge gaps related to safety must be filled, thereby mitigating potential hazards and lowering barriers to widespread implementation. Hence, validating consequence models against experiments and establishing and disseminating knowledge and guidelines regarding hydrogen safety, especially for use in the general public, is of key importance for the future hydrogen society.

Hydrogen is not necessarily less safe than other fuels, provided it is handled according to its unique properties. Hydrogen has a wide flammable range and very high rate of combustion, compared to conventional fuels. Hazards in hydrogen applications are typically related to leakage with subsequent ignition, resulting in fires, gas explosions and possibly rupture of pressurized vessels. The safety mechanisms of hydrogen tanks are critical, and various scenarios related to function, and the consequences of malfunction of pressure relief valves have been investigated [1-2]. A fire test demonstrated that tanks with disconnected valves can explode with a pressure wave strong enough to break glass windows 23 m from the epicentre, producing a 24 m diameter flame ball with emissivity of 340 kW/m2 [3]. A test from 2010 demonstrated that pressure relief valves based on threshold temperatures were inefficient if tanks were locally heated by a flame [4]. Much work has been done on hydrogen safety [5-9], and several knowledge gaps related to hydrogen hazards have been identified [6, 10-12]. However, there is still critical lack of knowledge and relevant experimental work related to fires and explosions involving hydrogen in environments that require highly conservative approximations, such as tunnels, ships and other enclosed spaces [11, 13, 14]. The HySafe HyTunnel project was established to evaluate hazards related to hydrogen vehicles in the confined space of a tunnel, and concluded that the consequence of hydrogen released inside a tunnel was significantly more severe compared to less confined conditions [15]. A related CFD study concluded that the pressure wave from a hydrogen explosion in a tunnel is significantly higher than from other gases and that a hydrogen jet fire can cause severe damage to a tunnel infrastructure and induce a possibility of igniting other cars. [15-17], but verification by relevant experimental work is lacking.

Liquefied hydrogen (LH2) is preferable for transportation and usage of large quantities of hydrogen. LH2 loss of containment (LoC) due to possible vessel damages may lead to Rapid Phase Transition (RPT) of the LH2 or Boiling Liquid Expanding Vapour Explosion (BLEVE). Both phenomena result in physical explosions: LH2 departs from a metastable state, induced by the LoC, to the equilibrium state of vapour, suddenly increasing its volume and leading to an overpressure wave. RPT has occurred as LNG has been spilled onto water [18] and BLEVE is a well-known phenomenon [19] for different substances such as water, propane, Liquefied Petroleum Gas (LPG) and LNG itself. Such experience has shown that the phenomena occurrence is characterised by a certain complexity. RPT is usually divided in early and delayed. The first one occurs during the release, close to the spill point, while the second one is not instantaneous and develops in different parts of the spreading pool [20]. Experts also distinguish between subcritical and supercritical BLEVEs, based on the containment pressure being, respectively, lower and higher than the substance critical pressure [21]. There are no records about RPT accidents for LH2. Theoretically, RPT may occur also for LH2 since it is a cryogenic fluid and its mixing with normal temperature fluids may lead to explosive evaporating [22]. On the other hand, a LH2 BLEVE occurred in 1974, as a result of improper firefighting. To extinguish a fire, firefighters water-sprayed a tank vent stack, which froze and sealed the tank. The contained hydrogen subsequently warmed up and increased the internal pressures, causing a BLEVE explosion [23]. Given the little knowledge on the possibility and mechanisms of LH2 RPTs and BLEVEs, it is important to investigate and improve the relevant models used for their risk analysis. Although there are substantial limitations in the methods for assessing related consequences and probability [24], acoustic models and integration of thermal and mechanical models have produced promising results for other hazardous substances [25, 26].

To ensure safe operations, operators and industry require tools for consequence analysis and risk assessment that are sufficiently accurate and validated for realistic scenarios. There are several available qualitative and quantitative tools and methods for use in hydrogen risk assessments [27], including HyRAM from Sandia [28] and models based on computational fluid dynamics (CFD). Although fire and explosion hazards in hydrogen applications are reasonably well addressed in industry, the risk and consequences may be different for incidents in the transport sector and in enclosed spaces such as tunnels and ships. In 2014, HySafe (The International Association for Hydrogen Safety) published a report [28] that identified a need for research to establish user-friendly, industry-focused software tools to enable risk-informed decision making, and also pointed out a lack of validated models of barrier behaviour, which is highly relevant to incidents in enclosed spaces. Furthermore, the relevance of existing methods to evaluate risks for scenarios involving a combination of fuel types (e.g. CNG, H2, gasoline, charging of electric vehicles) should also be evaluated. A blind-prediction study involving vented hydrogen explosions in 20-foor ISO containers, conducted as part of the HySEA project (www.hysea.eu), demonstrated a dramatic spread in the results obtained with different consequence models [29]. Safe and widespread implementation of hydrogen in society will require significant progress in the predictive capabilities of such models.

2.0 THE SH2IFT PROJECT

2.1 Introduction

The SH_2IFT project shall increase competence within safety of hydrogen technology, especially focusing on consequences of handling and use of large volumes and within closed and semi-closed environments and in maritime transport. Relevant aspects from the whole value chain from industry and authorities to end users/general public will be investigated, with special emphasis on the potential obstacles and bottlenecks for early implementation of hydrogen as fuel. The project will both develop new models, perform large-scale fire and explosion experiments, and provide guidelines for use of hydrogen in industry and transport.

2.2 Research questions to be addressed

This project investigates the main concerns and potential barriers to the implementation, handling and use of hydrogen technology and infrastructure in Norwegian society (industry/government/general public). A technological innovation systems approach to socio-technical transitions is applied. Current knowledge gaps related to safe handling of LH2 and GH2 (gaseous hydrogen) will be addressed by experiments giving new knowledge and understanding related to consequences of possible incidents. Focus will be given to RPTs, BLEVEs and jet fires. The relevance of currently used risk and consequence modelling tools will be evaluated for the chosen scenarios related to current knowledge gaps. Fire and explosion tests will be applied in order to validate new developed theoretical models. National and international regulations, standards and procedures will be evaluated, and recommendations will be proposed based on new findings in the project.

3.0 FIRE AND EXPLOISION EXPERIMENTS

3.1 Jet fires

Tests will be conducted to study characteristics of gaseous hydrogen flames, and the effect on fire barriers, gas containers and safety mechanisms in realistic fire scenarios in (semi-) closed space and multi-fuel environments. Impinging jet flames, recirculated flames and high temperature fires will be studied, using a setup with a gas jet nozzle. The scale of the experiment will be based on a relevant GH2 storage system with safety release mechanisms. Instrumentation will ensure measurements of the thermal exposure to objects that are engulfed and impinged by the jet fire. The purpose of the experiments is to quantify the severity of a fire involving a GH2 tank in a bus terminal, tunnel, underground parking house or other enclosed spaces. The tests will be repeated with other fuel(s) for comparison and to simulate a multi-fuel environment.

3.2 RPT and BLEVE

During the 1980s, several RPT tests for LNG on large scale were carried out in the USA by the Lawrence Livermore National Laboratory (LLNL) [30], [31]. In 1997, LH2 was spilled onto water to study the pool spread [32]. These tests were carried out by Forschungszentrum Jülich (FZJ) in the BAM facilities (Cottbus, Germany). Unfortunately, during these tests, RPT did not occur, probably due to the limited LH2 flow rate and water volume [33].

Several BLEVE tests have been carried out in the past for various substances such as LPG and LNG [34]. In the 1990s, BMW carried out several safety tests on a LH2 tank developed for the BMW Hydrogen 7 model [35]. One of these test series consisted in a fire test. During this test, the LH2 tank was completely engulfed in the fire. After 14 minutes, all the hydrogen contained in the tank evaporated flowing through the pressure release valves (PRVs) [36]. This was the only LH2 tank fire test realized in the past and BLEVE has not been reached.

These past experiences highlight the need for further specific experimental tests. RPT and BLEVE tests will be conducted to investigate BLEVEs from vessels containing LH2 hydrogen and to look into the possibility of the generation of RPTs by releasing LH2 onto water. For the latter experiments liquefied hydrogen is introduced as a jet onto the water in a basin. The basins and its surroundings would be heavily instrumented to perform temperature-, blast- and gas concentration measurements. High speed camera will in addition be used to monitor the RPT development and weather conditions will be measured. The BLEVE experiments will be performed on a similar scale as the RPT. A controllable and known fire loading will be used for achieving BLEVE conditions. The experiments will address the blast pressure generated, the fire ball dimensions, fire loading parameters (convective and radiative loading) as well as missile generation. Temperature conditions inside the bottle will be measured as well.

4.0 MODELLING TOOLS

4.1 Gaseous hydrogen

The objective here is to fill knowledge gaps about fire safety of GH2 transport and use, and improve established risk and consequence modelling tools for GH2-related scenarios. The modelling tools that will be investigated are FLACS, HyRAM and various integral models. Knowledge gaps and strength/weaknesses in modelling tools will be laid bare for relevant scenarios, focusing on how hydrogen, as well as containers and safety mechanisms, behave in the extreme conditions that may occur in fires in (semi-)closed space and in multi-fuel environments. Both small and large hydrogen volumes will be included in the study. The selection of relevant volumes will be based on the capacities that will be used in small and large vehicles, trains and ships and transport tanks for road and rail. Simulations will be compared to results from experiments performed.

4.2 Liquid hydrogen

This work focuses on consequences of the loss of containment of liquid hydrogen. In particular, the consequence prediction of RPT and BLEVE will be improved through application of experimental results to in-house simulation tools. The developed models will be used to simulate the LH2 RPT and BLEVE experiments. Comparison of the respective results will suggest modelling improvements. Based upon spill rate, water temperature and degree of mixing between LH2 and water, the RPT model will estimate the explosion probability and quantity of LH2 in the vapour explosion. Based upon the amount of LH2 stored and vessel characteristics, such as coating and pressure relief valves, the BLEVE model will assess thermal and mechanical response of the vessel and it's time to catastrophic failure when exposed to fire. For both the events, the explosion overpressure in function of distance will be modelled based on the analysis of blast waves. Based on results, the study will ultimately allow the definition of appropriate technical safety barriers, such as passive fire protections and design of pressure resistant systems.

5.0 SOCIETAL CONCERNS, BARRIERS AND GUIDELINES

The objective this activity work is to reveal and understand concerns and potential barriers in the Norwegian society regarding introduction of hydrogen technology. A multi-method approach [40], integrating existing data with novel survey and interview data will be used. In-depth interviews with key actors will be carried out with stakeholders at the national and local level. In addition, focus group interviews and a stated-preference survey, targeted at the general public, will be conducted.

Based on all results, the aim is to develop recommendations with respect to the use of risk analysis and modelling tools, as well as guidelines and procedures for handling gaseous and liquid hydrogen for both industrial and public use. These will be based on existing information, national and international, and new knowledge gained throughout the project.

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