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Explosion free in fire self-venting (TPRD-less) Type IV tanks: Validation under extreme impinging 70 MPa hydrogen jet fire conditions

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HIGHLIGHTS

- The concept of explosion free in fire self-venting (TPRD-less) tank is discussed.
- Self-venting operation of 70 MPa tank is demonstrated in extreme jet fire conditions.
- Tank did not rupture but leaked under realistic impinging hydrogen jet fire (70 MPa).
- Jet fire of largest known specific heat release rate of HRR/A = 19.5 MW/m^2 was applied.
- The technology has the potential to exclude tank rupture in fires onboard of trains, ships, etc.

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ABSTRACT

High-pressure hydrogen jet fire from a storage tank impinging another tank located nearby is a worst-case incident scenario. This could result in storage vessel rupture with catastrophic consequences implying life and property loss. The concept of microleaks-no-burst (μLNB) performance of hydrogen storage tanks of Type IV is explained. In this study, the breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tank with nominal working pressure (NWP) of 70 MPa is validated again st the most extreme fire conditions of an impinging hydrogen jet from 70 MPa tank. The results of the successful performance of self-venting tank in momentum-dominated hydrogen impinging jet fire are analysed. This work expands further the experimental validation domain of the explosion free in fire self-venting tanks to scenario of impinging fire of the highest applied intensity of HRR/A = 19.5 MW/m^2.

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1. Introduction

Hydrogen-powered cars, buses, trucks, trains, ships, and planes are being deployed in countries around the world alongside battery electrical vehicles. This is an unavoidable way forward for mankind due to the scarce oil and gas resources that will not last long at the current rate of consumption. Along with that, by 2050, if utilised at scale, hydrogen might make up close to 1/5 of the overall final energy consumption. This represents around 20% of the reduction efforts needed to keep global warming to 2 °C and reduce annual CO2 emissions by about 6 Gt compared to today's levels [1]. Future hydrogen demand is expected to increase, hence hydrogen generation should be assessed to meet industrial sectors' needs [1,2]. A critical "plank" in the UK government's strategy to "build back better" through a "cleaner, greener energy system" is the development of a thriving hydrogen industry, and they have ambitious goals to achieve steady hydrogen production output reaching 5 GW per year by 2030 [3]. Around the world, numerous hydrogen production plans are beginning to receive funding from other governments and companies, including those in the US, Europe, Asia, Australia and China [4].

Since the Hindenburg disaster the main concern of the public is still "hydrogen explosions", which in fact was not the case for Hindenburg as there was simply diffusive combustion of hydrogen when the dirigible highly flammable material of its shell was ignited and lost its integrity. To the best of the authors' knowledge, currently there are only a couple of studies on the quantitative risk assessment (QRA) of hydrogen-powered vehicles for scenarios of onboard storage tank rupture in a fire [5,6]. These QRA studies demonstrate that for the case of hydrogen cars on London roads and in the Dublin Tunnel, the risk is acceptable if the fire resistance rating (FRR) of onboard tanks, i.e., the time from a fire start to tank) rupture, where the thermally activated pressure relief device (TPRD) failed to be initiated by a fire, is above FRR = 50 min and FRR = 90 min respectively. Other studies, e.g., on risk for the fuel cell forklifts [7], unfortunately, did not investigate the scenario of hydrogen storage tank in a fire and did not assess its FRR.

It was demonstrated that the risk for ordinary tanks with the short FRR of about 4–8 min is unacceptably large compared to the 10^{-5} acceptance criterion [1,2]. These QRA studies are applicable to the instances of traffic-related incidents escalating to gasoline/diesel spill fires with characteristic specific heat release rate of HRR/A = 1–2 MW/m^2 [4,5]. Here, HRR/A is the ratio of the heat release rate in a fire, HRR, to the area of a fire (burner), A. The fact that the GTR#13 fire testing procedure permits only significantly reduced localised fire intensity of HRR/A = 0.3 MW/m^2 [6,7], makes the matter more difficult, as it is far from the realistic 1–2 MW/m^2 representative of fossil fuel spill fires [8]. There are numerous real possible instances of fires that could have different intensities and that could happen to a hydrogen-powered vehicle. They range from low intensity smouldering fires [9–11], through medium intensity nearby vehicle fires, including fuel spills [4,5,8] and tyre fires [12], to extreme scenario of thermal aggression from a jet fire [13–20], that could erupt from an adjacent vehicle or the vehicle involved in the same incident, whether it is a release from TPRD or a damaged high-pressure piping, etc.

The QRA studies mentioned above demonstrated that compressed hydrogen storage systems (CHSS) equipped with TPRD cannot provide acceptable level of risk for the following reasons: the TPRD does not react to localised fire; it does not react to low intensity fires of different commodities and smouldering fires; the TPRD can be blocked/shielded from the fire in an incident; it could have unacceptably long response time especially for conformable tanks with FRR of about 2 min, due to their thinner walls, while TPRD response time could be longer, e.g. 2.5 min.

TPRDs have comparatively high non-zero failure probability as per published data [5]. Pressure relief devices are considered by some companies as a potential incident trigger for gas cylinders and thus not recommended. It is hard to imagine a thermal protection system of CHSS composed of several tanks that could stand 90 min of fire and will not add cost, size and weight of the storage which are critical parameters for any CHSS especially onboard of vehicle, train, ship, etc. Reported in literature FRR of currently used standard tanks is 4–12 min depending on the HRR/A. The lower is the HRR/A the longer is the FRR [8].

One solution to the aforementioned problems of CHSS with TPRD is the explosion free in any fire self-venting (TPRD-less) tanks exploiting the microleaks-no-burst (μLNB) safety technology. The exclusion of high-pressure tank rupture in fire of any intensity, including real fires (with higher specific heat release rate above the unreasonably reduced values in GTR#13 [21]), is of paramount importance to provide life safety and property protection at an acceptable level of risk. Then, the risk of a tank rupture in a hydrogen-powered vehicle in the event of a fire incident could be expected to be below that for current fossil fuel vehicles. To date 14 prototypes of explosion free in fire self-venting tanks at nominal working pressure NWP = 70 MPa were successfully tested. The research on performance and validation of the μLNB safety technology for carbon-carbon and carbon-glass double-composite wall hydrogen storage systems prototypes is described in our first paper [22], and the technology performance in conditions of fire intervention in the second paper [23].

This paper is the third in a series of publications on the breakthrough safety technology of explosion free in a fire self-venting (TPRD-less) hydrogen storage tanks. It demonstrates the performance of μLNB tank in extreme conditions of hydrogen impinging jet flame. Indeed, the results of HyCOMP project demonstrated that hydrogen fire is a worst case scenario in sense of lowest FRR [24] due to the highest specific heat release rate of HRR/A = 7.4 MW/m^2 applied in fire testing of composite tanks with hydrogen-oxygen burners [8]. However, this HyCOMP fire test was not using high-pressure hydrogen storage tank to impinge tested tank. Higher adiabatic temperature of hydrogen combustion compared to other fires is another argument of the extreme conditions of composite vessel testing in hydrogen jet fire as it could melt/degrade fibres able to withstand lower temperatures. High-pressure hydrogen jet flame from a storage tank impinging nearby storage tank is a possible incident scenario in storage enclosures of hydrogen-powered trains, ships, planes, as well as onboard cars, buses, trucks, etc. This incident scenario with hydrogen storage has not been investigated up to now.

This paper describes the concept of microleaks-no-burst performance of Type IV tanks in fire and analyses the experimental performance of the self-venting (TPRD-less) NPW = 70 MPa tank in the extreme conditions of impinging hydrogen jet fire from CHSS at 70 MPa located nearby imitating an unscheduled under-expanded hydrogen jet fire, e.g., from TPRD or piping.

2. The microleaks-no-burst (μLNB) safety technology

Fig. 1 (left) explains the performance of a standard composite tank of Type IV in a fire. The composite wall of the tank is made of one material. The liner limits hydrogen permeation to the regulated level [21] and the fibre reinforced polymer (FRP) wall bears the internal pressure of hydrogen. Under fire conditions the resin of the composite degrades, and fibre plies become loose where the resin is decomposed, therefore no longer able to bear the hydrogen pressure load. The resin degradation front propagates from outside into the wall (thick red line in Fig. 1). Pressure inside the tank grows in time due to heat transfer from the fire through the wall to the hydrogen. This results in the increase of the fraction of the wall thickness (dotted line in Fig. 1) needed to bear the load (minimum regulated safety factor for burst pressure is 2.25 of the nominal working pressure (NWP), i.e., only 1/2.25 = 0.44 fraction of the wall thickness can carry NWP load). The tank ruptures when the resin decomposition front propagating inwards reaches the load-bearing fraction of wall thickness, which is outwardly propagating in time.

Fig. 1 (right) shows the performance of μLNB tank in fire. The main difference in the μLNB tank design compared to the standard tank is it having two, not one, composites in the wall. The external composite is marked in Fig. 1 (right) as thermal protection layer (TPL) that has lower thermal conductivity and can be either load bearing, e.g., fibre-resin composite, or not, e.g., intumescent paint. The internal composite is marked as FRP and has higher thermal conductivity compared to TPL. The thermal parameters of liner, TPL and FRP and their thickness are selected in the way to melt the liner before the resin decomposition front reaches the load-bearing fraction of the wall (see the description of invention [15,18]), i.e., microleaks are initiated through the wall to exclude the tank's rupture. The microleaks initiated over the wall body quickly reduce the storage pressure eliminating the potential of tank rupture due to a decrease of wall thickness fraction needed to bear the pressure, which is reducing over time.

Leaking hydrogen either burns in tiny microflames with or without resin or, in case of release without combustion, quickly decays to concentrations below the lower flammability limit if the leak flow rate is below the flame quenching limit or above the blow-off limit [19,20]. The technology implies that when a fire is extinguished the microleaks would not create flammable atmosphere around the tank surface due to small size and discrete character of release. The technology was successfully validated in fires with realistic specific heat release rate of HRR/A = 1 MW/m^2 for different scenarios, including fire intervention [13,16]. However, the scenario of impinging hydrogen jet was not studied experimentally up to date even if the in-house modelling tools predicted that properly designed self-venting tanks should operate without rupture in fire with arbitrary HRR/A.

3. Description of the prototype and the validation experiment

The μLNB tank prototypes experimentally tested in impinging hydrogen jet fire in this study (see Fig. 2) were designed at HySAFER Centre of Ulster University using as the basis the original 7.5 L Type IV tanks with NWP = 70 MPa produced by our partner in the USA. Four series of μLNB tank prototypes were designed, manufactured, hydro- and fire tested [13,16] and the work is being done on a further three series of tanks, at the time this report was written. Each series had its own goal and each tank had unique characteristics, such as various liner materials, different fibres and resins specifications,

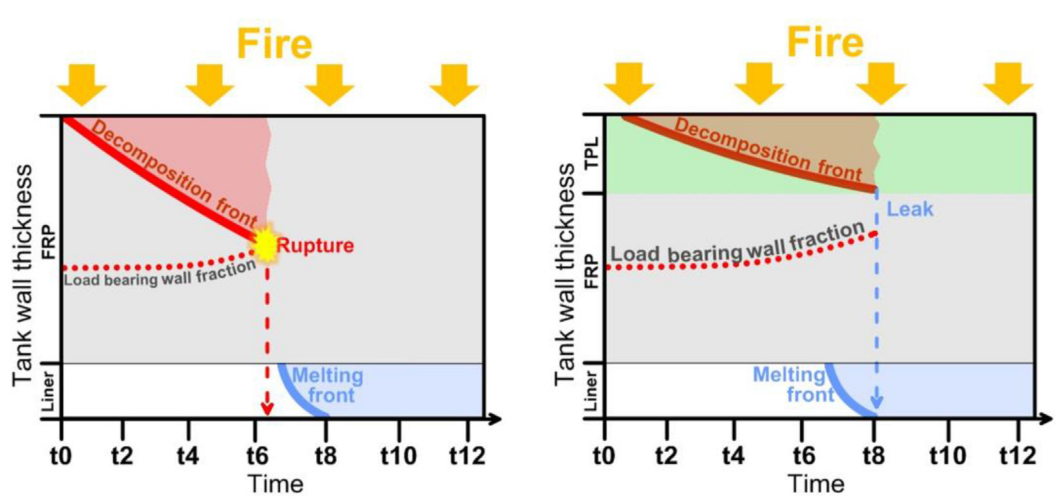


Fig. 1 – Explanation of μLNB safety technology for composite Type IV tanks: performance in a fire of a standard tank (left) and μLNB tank (right) [22,25].

Fig. 2 – The μLNB tank prototypes tested in this study.

ratios of two composite thicknesses, and diverse fire conditions, including extinction.

Table 1 describes the details of the prototypes, i.e., composite overwrapped pressure vessels (COPVs) with high density polyethylene (HDPE) liners, and composite overwraps, made of carbon fibre reinforced polymer (CFRP) and basalt fibre reinforced polymer (BFRP).

The test and simulations analysis presented in this paper refer to the prototype COPV#CB-1 only. Due to fire test software malfunction the hydrogen jet fire was unexpectedly stopped in test with COPV#CB-2. This limited duration jet fire has changed the important parameter of the μLNB tank design, i.e., the ratio of thicknesses of Layer 1 (FRP) to Layer 2 (TPL), see Fig. 2 in our paper [22]. Thus, the "design" parameters of the tank were altered. This is why fire test with COPV#CB-2 is not described in this study.

The hydro-static and hydro burst tests were performed at facilities on the manufacturer in the USA. The impinging jet fire test was undertaken inside the steel tunnel of the HyTunnel facility at Science Division of Health and Safety Executive (HSE) in Buxton (UK). The existing state-of-the-art infrastructure for hydrogen pressurisation, leak control, data logging, instrumentation, and video recording was used.

The hydrogen pressurisation system was used for both filling the test vessels and for the impinging jet of ignited hydrogen released from the nozzle. The hydrogen pressurisation system takes hydrogen from multi-cylinder packs (MCP) and boosts the pressure from the storage with pressure not more than 17 MPa, in a two-stage process, using three Haskell booster pumps to fill three, 53 L capacity, storage reservoirs with hydrogen to a pressure of 70 MPa. This reservoir is then used to fill the test vessel to the required pressure (NWP = 70 MPa) for the experiment. Once the μLNB prototype tank was filled and isolated, the hydrogen pressurisation system is switched into the jet release mode and then used to generate a high-pressure ignited hydrogen jet impinging against the test vessel. The impinging jet is ignited using a pyrotechnics gerb, which is controlled remotely.

Table 1 – Parameters of the two μLNB tank prototypes of 7.5 L and NWP = 70 MPa manufactured for testing in hydrogen jet fire.

Prototype	Liner	Layer 1 (FRP)	Layer 2 (TPL)	Outside D increase*
COPV#CB-1	HDPE	CFRP	BFRP	0%
COPV#CB-2**	HDPE	CFRP	BFRP	2%

Note: * - diameter of μLNB tank increase compared to the original tank; ** - fire test software malfunction, causing the jet fire test to stop prematurely by cutting hydrogen supply.

Fig. 3a and b shows the test vessel view from sides opposite and facing the release nozzle respectively. The prototype was mounted on to a custom-designed stand and positioned inside the tunnel at a height of 1 m off the concrete floor to the centre line of the vessel and 1 m away from its front surface to the nozzle release point. Fig. 3c and d demonstrate location of the high-pressure hydrogen jet release nozzle and its close-up view accordingly. A self-levelling laser spirit level was used to set the precise alignment of the nozzle relative to the test vessel (see Fig. 3e and f).

Thermal protection was applied to the pipework and transducers. The stand was bolted to the floor once alignment was confirmed. The test conditions were: vessel (front surface) to nozzle distance is 1 m; jet impingement to front centre of the vessel; initial vessel filled pressure equal to 70 MPa; initial pressure in the storage for hydrogen jet fire is 70 MPa; duration of test is of about 30 min; measured nozzle diameter is 0.71 mm.

The vessel was connected to the hydrogen filling system and transducers installed. The following instrumentation was installed into the test vessel and used during testing:

- Thermocouple (Type K, stainless steel sheathed, conforming to IEC 60584–3:2007/BS EN 60584–3:2008, class 1 tolerance) for monitoring the internal temperature of the test vessel, inserted axially into one of the end fittings of the tank and sealed using a Spectite™ high pressure, high temperature gland. The tip of the thermocouple was positioned to be central in the inner space of the tank.
- Flame and explosion proof pressure transducer Druck UNIK 5800 for monitoring the internal pressure of the test vessel.

These were additional transducers (Druck UNIK 5800) for pressure monitoring in the nozzle manifold (the central bore of which is 25 mm diameter and 220 mm long) of the stage 2 hydrogen storage tanks, inside the tunnel in the test vessel filling line.

The hydrogen jet fire resulted from blowdown of 159 L, 70 MPa storage system through the nozzle of 0.71 mm diameter. The jet was directed horizontally along the length of the tunnel. It was switched off after 22 min from the test start, i.e., a long time after the pressure in the μLNB tank drops due to microleaks to atmospheric pressure at about 15 min after the test start.

Fig. 4 shows four snapshots of the test at time 1 s, 3 s, 5 s and 21 s after its start. The first snapshot "1s" (Fig. 4a) demonstrates the initiation of the igniter used to ignite the hydrogen jet, and snapshot "3 s" (Fig. 4b) demonstrate the igniter fully operating. Snapshot "5 s" (Fig. 4c) shows how the leading edge of high-pressure hydrogen jet deviates the igniter flow towards the μLNB tank. The established hydrogen jet fire impinging the tank is seen in snapshot "21 s" (Fig. 4d) corresponding to the time when the igniter was stopped. The

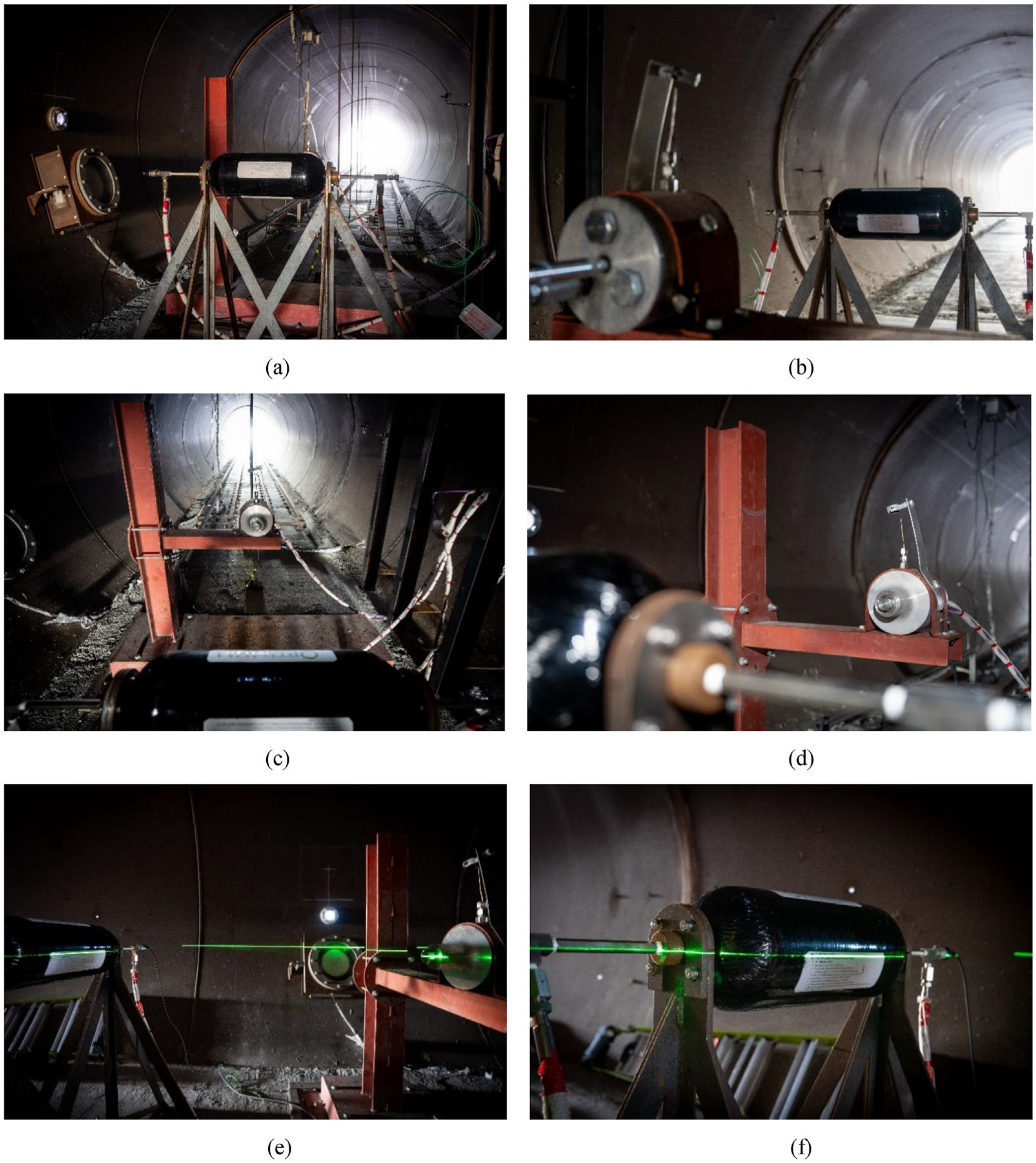


Fig. 3 – Experimental set: (a) and (b) - the μLNB tank prototype view from sides opposite and facing the release nozzle respectively; (c) and (d) - location of high-pressure hydrogen jet release nozzle and its close-up view; (e) and (f) - self-levelling laser spirit level for the precise alignment of the nozzle relative to the test vessel.

impinging jet fire covers all surface of the tank. The snapshots of the impinging hydrogen jet fire test progress are presented in the next section.

4. Results of the μLNB tank prototype fire testing and discussion

The use of "Jet parameters model" tool of the e-Laboratory of Hydrogen Safety (https://elab.hysafer.ulster.ac.uk/) underpinned by research [26,27] allows us to calculate the initial maximum mass flow rate of the hydrogen release from 70 MPa tanks though 0.71 mm orifice diameter as $\dot{m} = 13.51$ g/s. Multiplication of this mass flow rate by the hydrogen heat of combustion of 119.96 MJ/kg gives the heat release rate of such jet fire equal to HRR = 1.62 MW. The specific heat release rate, HRR/A, is he ratio of the total fire HRR over the area of the fire source, A [8]. Determination of the HRR/A of such impinging jet fire source is not trivial, as it is not straightforward what area of the fire source should be chosen. When considering a standard fire test protocol in regulation GTR#13 [21] or EC R134 [28], the fire source is the rectangular shaped burner, that consists of a localised portion (usually 0.25 m long) and engulfing portion (usually 1.4 m long, making the total burner length of 1.65 m), with the width encompassing the CHSS width. In such case determination of the burner area is straightforward. With the jet fire, it is unclear what is to name as the fire source, e.g., the pipe opening area, the tank projection area, or the area of the jet fire transversal cross-section near the tank. In case of the pipe opening, the area for its

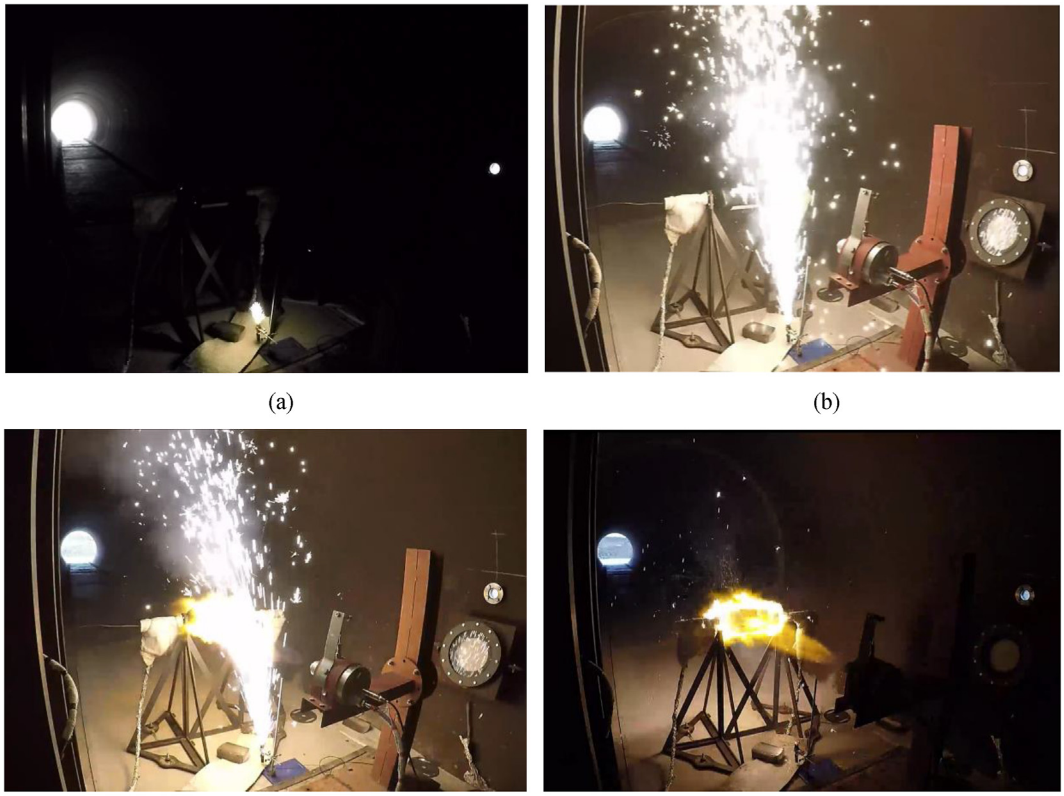
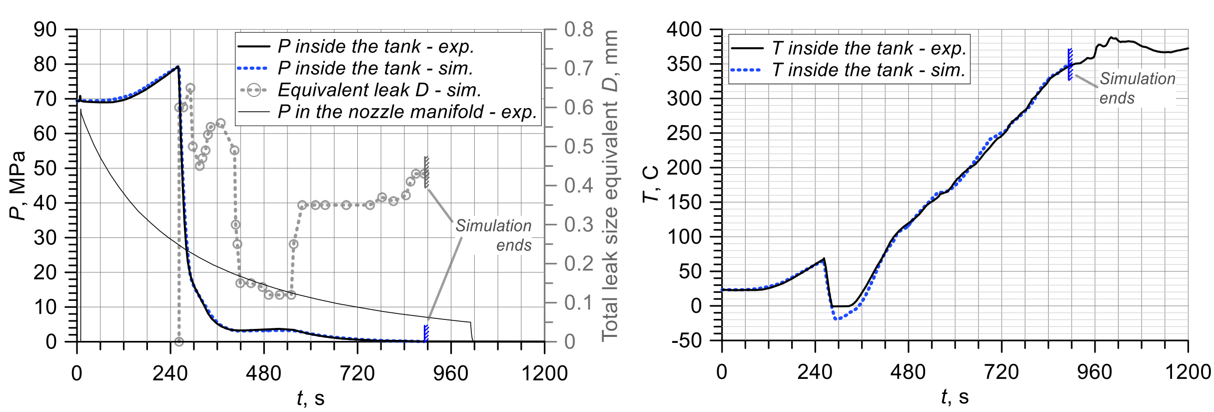


Fig. 4 — Snapshots of the fire test start: (a) — 1 s; (b) — 3 s; (c) — 5 s; (d) — 21 s.

0.71 mm diameter is A = 3.96^{-7} m^2, giving extremely large HRR/A = 1.62 MW/3.96 × 10^{-7} m^2 = 4.09 × 10^6 MW/m^2 = 4.09 TW/m^2. It is more reasonable to use the tank projection area A = 0.083 m^2, especially in conditions of impinging jet with diameter near the tank close to the tank diameter (see Fig. 4d). This results in HRR/A = 19.5 MW/m^2. This is the highest specific heat release rate ever reported in fire testing of CHSS.

Fig. 5 shows transients of parameters measured during this fire test at extreme conditions (hydrogen pressure and temperature inside the tank, pressure in hydrogen system before the jet nozzle) and simulated using in-house non-adiabatic blowdown model [8] (hydrogen pressure and temperature inside the tank, equivalent microleaks diameter). The inverse problem method was used to define changing in time equivalent diameter of microleaks as a sought parameter while



(a) (b)

Fig. 5 — Hydrogen pressure (a) and temperature (b) transients inside the μLNB tank. Pressure transient (thin monotonically descending curve at (a) graph) in front of the nozzle of the jet fire source.

reproducing in simulations measured pressure and temperature transients.

Fig. 5a shows the experimental pressure dynamics in the μLNB tank (thick solid curve), experimental pressure in front of the nozzle releasing impinging hydrogen jet (thin solid curve), simulated pressure transient in the tank (dashed curve) and defined by the inverse problem method the changing in time diameter of an orifice with area equivalent to the cumulative areas of all microleaks through the tank wall (grey dash curve with circular symbols). Fig. 5b shows the

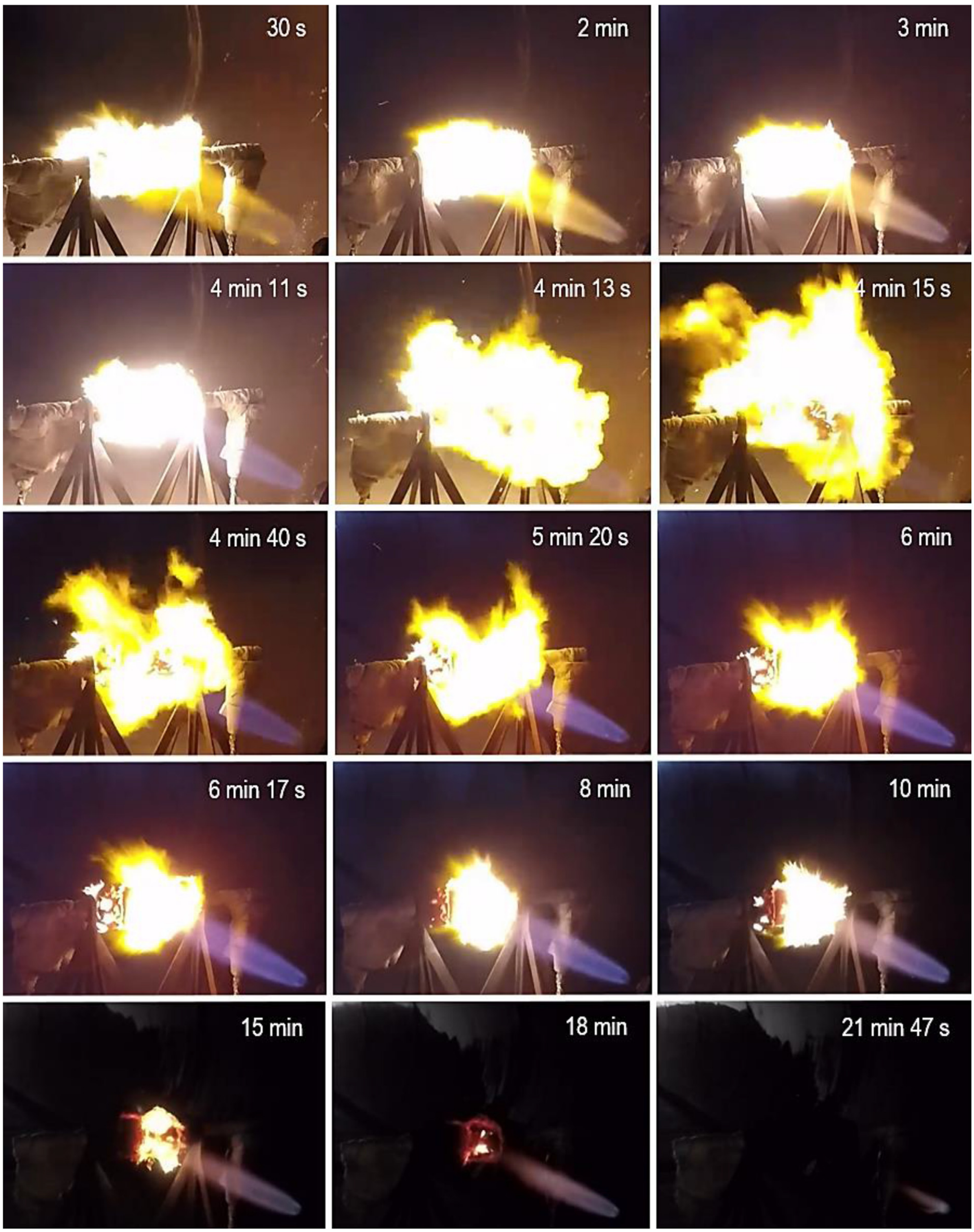


Fig. 6 – Snapshots showing the progression of the impinging hydrogen jet fire test.

experimental (solid curve) and simulated (dashed curve) temperature in the tank.

The initial pressure of hydrogen in the tank is 69.4 MPa. The pressure grows in the closed tank with the increase of temperature due to heat transfer from the fire through the tank wall to the hydrogen. The liner melts to initiate microleaks at time 4 min 12 s after the jet fire test start. At this time the pressure inside the tank has increased by 10 MPa–79.4 MPa and the hydrogen temperature has reached 65 °C (43 °C above its initial temperature of 23 °C). The microleaks reduce the pressure in the tank (see Fig. 5a) which, in turn, causes the drop of temperature due to expansion to almost −20 °C. The decreased temperature caused by the leaking of hydrogen through the microchannels could cool down and even freeze the plastic liner (HDPE liner crystallisation temperature is in the quite broad range of 80–120 °C [21,22]), however it does not close the gaps created during melting in the liner and therefore does not stop hydrogen release through microleaks. Cooled hydrogen can also "solidify" the resin of the composite at corresponding thickness (the glass transition temperature can vary widely between 75 °C and 135 °C [23,24], and the decomposition temperature is 370–380 °C [25,29]). There is a heating of hydrogen by Joule-Thompson effect caused by throttling of the gas flow through the microchannels which is somewhat compensated cooling of hydrogen inside the tank due to expansion.

The decrease of internal pressure during release could affect the efficiency of hydrogen release by assumed reduction of the size and number of microchannels due to the tank wall contraction. The contraction of the wall and decrease of temperature are followed by a plateau of measured pressure in the tank at about 6 min 30 s (see Fig. 5a). It is shown in our first paper in a series [22] that even the total equivalent area of microleaks reduces at the plateau, there release of hydrogen continues but with a smaller flow rate. This conclusion is confirmed by this study. The expansion of hydrogen after pressure drop is negligible and thus it does not influence temperature change. Contrary, the strong heat transfer from the high temperature impinging jet fire continues and is responsible for increase of hydrogen temperature inside the storage tank. The pressure drop after the plateau corresponds to hydrogen temperature increase to about 150 °C that is sufficient to melt the entire liner. In addition to this, jet fire continues to decompose the composite resin that could support creation of new microchannels in the wall of continuously decreasing load-bearing thickness. The pressure in the tank drops to atmospheric at time 15 min. Because the impinging jet fire was affecting the tank afterwards, the temperature inside the tank continues to grow and is "stabilised" at 360–390 °C that corresponds to the resin decomposition temperature. Hydrogen temperature cannot exceed this temperature unless the impinging jet erodes the tank wall through and directly penetrates the tank. It was not the case in this test. The impinging jet fire was terminated at 21 min 47 s. The tank started to slowly cool down and hydrogen temperature in the tank began to drop too.

The simulations of the pressure (Fig. 5a) and temperature (Fig. 5b) inside the tank were carried out using models of hydrogen storage tank non-adiabatic blowdown [8] and its performance in a fire with account of phase changes in resin of composite and liner [30]. The inverse problem method was applied to reproduce both pressure and temperature in a vessel by selecting the total area of microleaks, which changed in time. Both simulated pressure and temperature demonstrate a very good agreement with the experimental data, including the pressure plateau. The temperature plateau between 285 s and 330 s shown in the experimental data at around 0 °C is due to the range of the temperature transmitter being exceeded and hence why the simulated temperature deviates from it by up to 20° in that period.

Fig. 5a shows the dynamically changing equivalent leak diameter (imaginary orifice with area equal to the sum of actual microleaks area), which is defined in simulations. The orifice varies from about 0.60 to 0.65 mm at the start of the leakage. Then, due to composite shrinkage with pressure drop, the equivalent orifice diameter reduces to 0.15 mm and then to its minimum of 0.12 mm. The diameter varies within these values for about 2 min. The orifice diameter never drops below 0.12 mm, i.e., there is hydrogen leaking even when the pressure plateau is observed.

Fig. 6 demonstrates snapshots of the impinging jet fire test progression. The first four snapshots ("30 s", "2 min", "3 min" and "4 min 11 s") shows the μLNB tank under impinging hydrogen jet fire from 70 MPa tank with assessed extreme specific heat release rate of HRR/A = 19.5 MW/m^2 before the microleaks are initiated by liner melting. The technology provides release of hydrogen from the tank through microleaks at 4 min 12 s (snapshot "4 min 11 s" is just before the leak starts, and snapshot "4 min 13 s" just after the microleaks begin). At this time the pressure in the tank had increased from an initial 69.4 MPa–79.4 MPa, and the hydrogen temperature in the tank at the location of the thermocouple from 23 °C to about 65 °C. This is a larger increase of pressure compared to the experiments with propane burner with HRR/A = 1 MW/m^2, e.g., from about 70 MPa to 76.0–77.8 MPa (as described in our previous studies [22,23]), instead of the impinging hydrogen jet "burner" in this experiment.

The maximum size of the visible combustion zone in this test is shown by snapshot "4 min 15 s". It does not exceed regulated 0.5 m and continuously decreases to zero at the end of the release and afterwards (see snapshots "15 min" and "18 min" respectively). The impinging jet fire is terminated

Fig. 7 – Photo of the tank after the impinging hydrogen jet fire test.

when the pressure in the tank was equal to atmospheric for a while and the pressure in the fire source dropped to 5.7 MPa.

Fig. 7 gives a photo of the tank after the extreme fire testing by impinging hydrogen flame. Not only is the resin of the TPL composite layer decomposed but also several plies made of basalt fibres. It is worth mentioning that the decomposition temperature of basalt fibres is above 900 °C [31], i.e., higher than that for carbon fibres, ranging from 540 to 620 °C [27,28].

5. Conclusions

The *originality* of this work is in the use of numerical and experimental methods to demonstrate the reliability of design methods and performance of the breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tank at extreme conditions of impinging hydrogen jet fire from 70 MPa storage located nearby.

The *significance* of the study is in provision of the innovative engineering solution for composite storage tanks of Type IV able to withstand a fire of any intensity, e.g., impinging jet fire from one storage tank to another storage tank in the same compressed hydrogen storage system. By prevention of tank rupture in a fire, the microleaks-no-burst safety technology eliminates catastrophic consequences of incidents with tank rupture, i.e., devastating blast wave, fireball and projectiles, and thus saves lives and protects property even at severe thermal loads of fire with specific heat release rate of HRR/A = 19.5 MW/m^2. The work demonstrates that there is a novel technology for hydrogen storage tanks that can withstand fire of any intensity without rupture and does not require the use of TPRD to avoid associated issues like localised fires, etc. The existence and validation of the technology allows to change the regulation and test CHSS in extreme yet realistic fire conditions, including impinging hydrogen jet fire, to better protect customers and public from "hydrogen explosions". This would underpin and widen public acceptance of hydrogen-powered transport and refuelling infrastructure.

The *rigour* of this research is underpinned by the experimental validation of the μLNB tank design done by unique models developed at Ulster University. The numerically designed tank successfully passed the extreme fire test as predicted by this breakthrough safety technology with distributed hydrogen leakage through the wall not a rupture.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Clean Hydrogen Partnership. Neither the European Union nor the Clean Hydrogen Partnership can be held responsible for them.

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