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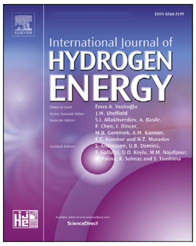

Explosion free in fire self-venting (TPRD-less) composite tanks: Performance during fire intervention

V. Molkov, S. Kashkarov*, D. Makarov

Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, Jordanstown, Newtownabbey, BT37 0NL, Northern Ireland, UK

HIGHLIGHTS

- Performance of self-venting (TPRD-less) tanks during fire intervention is studied.
- Examined fire intervention scenarios: removal from fire, fire extinction by water.
- Microleaks-no-burst carbon-carbon and carbon-basalt tanks tested in fire.
- Self-venting tanks allow standard fire intervention strategies and tactics.

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ABSTRACT

This paper describes the performance of explosion free in fire self-venting (TPRD-less) composite tanks in fires of realistic specific heat release rate (HRR/A), i.e., total fire HRR over the source area, A, of $HRR/A = 1\ MW/m^2$, during fire intervention. This breakthrough safety technology does not require thermally activated pressure relief devices (TPRD). It provides microleaks-no-burst (μLNB) performance of hydrogen storage tanks in fire. The study investigated two fire intervention strategies, i.e., removal of vehicle with μLNB tank from the fire, and extinction of fire by water. One carbon-carbon and one carbon-basalt double-composite wall tanks were assessed in the removal from fire scenario. Four carbon-basalt prototypes were studied in fire extinction scenarios. All six prototypes of 7.5 L and nominal working pressure of 70 MPa have demonstrated safe release of hydrogen through microchannels of the wall after the liner melting. The μLNB technology allows to apply standard intervention strategies and tactics.

Introduction

Rupture of high-pressure hydrogen storage tanks must be excluded in any fire scenario to eliminate hazards from blast wave, fireball, projectiles. The tank rupture consequences are different in the open [1–3] and confined spaces, like tunnels, where the blast wave decay is weaker [4,5], and thus drastically affects hazard distances.

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* *Corresponding author.*

E-mail addresses: v.molkov@ulster.ac.uk (V. Molkov), s.kashkarov@ulster.ac.uk (S. Kashkarov), dv.makarov@ulster.ac.uk (D. Makarov).

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List of acronyms

BFRP	basalt fibre reinforced polymer
CB	carbon-basalt
CC	carbon-carbon
CEA	French Alternative Energies and Atomic Energy Commission
CFD	computational fluid dynamics
CFRP	carbon fibre reinforced polymer
CHSS	compressed hydrogen storage system
CNG	compressed natural gas
COPV	composite overwrapped pressure vessel
FRP	fibre reinforced polymer
FRR	fire resistance rating
GTR	Global Technical Regulation
HDPE	high-density polyethylene
HRR	heat release rate
HRR/A	specific heat release rate
L	liner
μLNB	microleaks-no-burst
NWP	nominal working pressure
PA	polyamide
PPP	pressure peaking phenomenon
SoC	state of charge
TPL	thermal protection layer
TPRD	thermally activated pressure relief device
USN	University of South-Eastern Norway

The use of conceived at Ulster University the breakthrough safety technology of explosion free in a fire self-venting tank [6,7] will provide an unprecedented level of life safety and property protection. This would reduce hazards and associated risks of hydrogen-powered vehicles to the level equal to or below that for fossil fuel vehicles. The technology does not require thermally activated pressure relief device (TPRD) which can be unreliable in localised fires. For example, the FireComp project suggests 50% TPRD failure probability in localised fires [8], as it gets remote from the flame and hot combustion products. This was seen in cases with compressed natural gas (CNG) tanks with installed TPRDs [9–11]. Even in an engulfing fire, the catastrophic failure of the tank with TPRD is possible, e.g., if conformable hydrogen tanks are considered. The estimated time to rupture of such tanks with thinner walls in a fire is about 2 min, which is comparable with TPRD activation time in a fire [12] or even shorter than that (reported TPRD activation time reached up to 3.5 min in an engulfing fire [13]). The innovative safety technology provides the microleaks-no-burst (μLNB) performance of Type IV tanks in a fire [6,7]. The detailed concept and initial experimental validations of the technology for several carbon-carbon and carbon-glass double-composite wall μLNB tank prototypes are described in our first paper [6] in a series of forthcoming publications on this breakthrough safety technology. This is the second paper in a series that is focused on experimental studies of μLNB tank performance in conditions of fire intervention.

Incident fire scenarios and the importance of correct fire intensity in the fire test protocol

There is a wide range of real fire scenarios which could have different intensity. These are ranging from comparatively low temperature smouldering fires [14–16] through the vehicle tyre fire and liquids fuel spill fires [17–19] to extreme scenarios of impinging hydrogen jet fires [20], which could be a scenario, e.g., a jet erupting from nearby storage tank. Although there is a number of studies on the hydrogen jet fires from hydrogen storage systems [13,21–24], such a fire scenario falls outside of the scope of the present paper and will be investigated in our next paper on the μLNB tank safety technology. The fire intensity is characterised by the specific heat release rate, HRR/A, which is the ratio of the fire heat release rate, HRR, to the fire area, A. The fire resistance rating (FRR) is defined as a time to rupture in a fire for a storage tank or compressed hydrogen storage system (CHSS) with failed to be activated, e.g., by smouldering fire or a localised fire, or blocked from a fire during incident TPRD. There is a number of numerical and experimental studies on the tank performance in a fire, where ruptures of standard tanks were the prominent outcomes [2,5,20,21,25–30].

Figs. 1 and 2 show the results of experimental and numerical studies on the dependence of FRR as a function of HRR/A (blue strip). The FRR decreases with HRR/A. It does not practically change for HRR/A≥1–2 MW/m^2 characteristic for gasoline/diesel spill fires. Hydrogen regulations and standards, e.g., GTR#13 [31], require fire testing of CHSS following the protocol. The prescribed currently by the regulation values of HRR/A are below those for typical real fires such as gasoline/diesel spill fires. The reason is explained below. However, the authors believe that hydrogen storage tanks should be able to withstand any fire without rupture, not only fires of lower intensities. This has become possible by virtue of the μLNB safety technology.

The GTR#13 fire test protocol includes two stages, i.e., the localised fire stage of 10 min duration with the suggested HRR/A = 0.3 MW/m^2 followed by the engulfing fire stage with allowable HRR/A = 0.7 MW/m^2 [38]. These values of HRR/A are both below typical for gasoline fires HRR/A = 1–2 MW/m^2 [17–19,32] not to mention hydrogen jet fires, e.g. Ref. [20], of an order of magnitude higher than gasoline fires.

Fig. 1 explains how the use of a lower HRR/A prescribed by GTR#13 fire test allows the CHSS to pass the qualification test. However, the reduced HRR/A could mislead on what FRR of a hydrogen tank can be, for example in case when the HRR/A is increased to 1 MW/m^2 or above. The fire of intensity HRR/A = 0.2 MW/m^2 will result in FRR = 24 min. This time is longer than the localised fire stage duration of 10 min (see the bottom right insert in Fig. 1). During the localised fire stage, a tank is exposed to this fire and TPRD is not. Thus, after 10 min of the localised fire, the engulfing fire will begin to thermally affect the entire CHSS, including the TPRD. The TPRD, with a delay equal to its response time to the fire of this concrete intensity, will start hydrogen release from the tank and, if sized properly, will prevent tank from a rupture. However, the above is valid only for low intensity fires.

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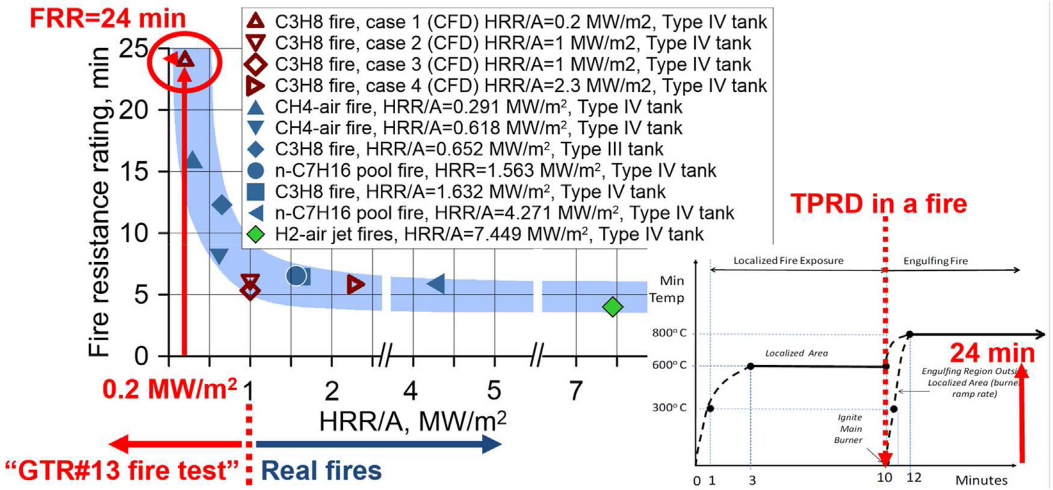

Fig. 1 – Dependence of FRR on HRR/A demonstrating that in a fire of low intensity HRR/A = 0.2 MW/m^2 the FRR = 24 min, i.e., longer than the localised fire duration (see the insert at the right bottom corner) [20,21,30,31,32–37].

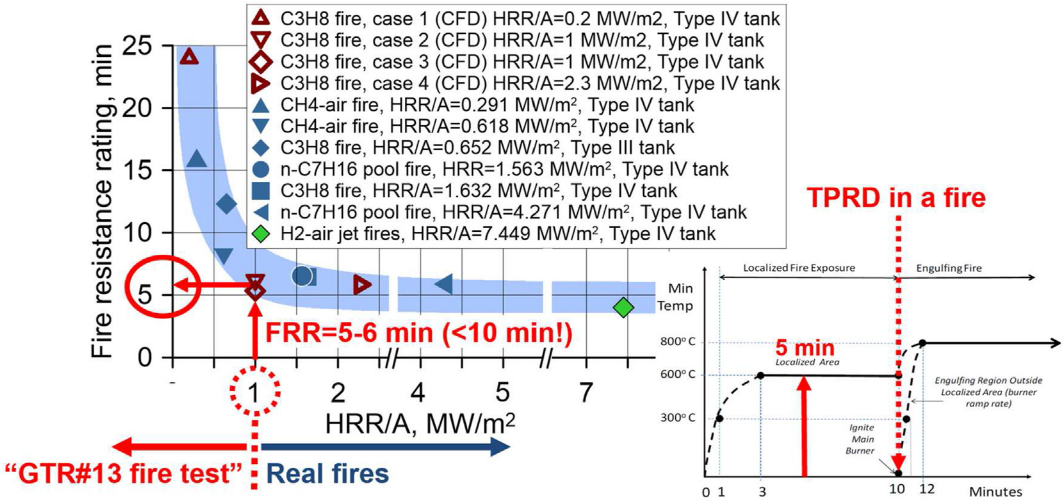

Fig. 2 – Dependence of FRR on HRR/A demonstrating that in a fire of typical for gasoline spill fire intensity of HRR/A = 1 MW/m^2 the FRR = 5–6 min, i.e., shorter than the localised fire stage duration (see the insert at the right bottom corner) [20,21,30,31,32–37].

The situation changes drastically if the same tank is in a fire of a higher intensity, e.g., gasoline/diesel spill fire of HRR/A = 1–2 MW/m^2 after a traffic incident. Fig. 2 shows that in such a fire intensity the tank could rupture in 5–6 min, i.e., before the TPRD is affected by the engulfing fire (see the insert at the bottom right corner of Fig. 2). This can create unacceptable hazards and associated risks for life and property in fires of higher intensity. It is thus understandable, that the fire test protocol suggested in GTR#13 could have serious life safety implications in real life, especially for the first responders, and must be amended to include fires of higher intensity.

The analysis presented in this section demonstrates that the fire test protocol of GTR#13 should be changed to include fire intensity of HRR/A = 1 MW/m^2 to underpin the safety of hydrogen storage tanks in real life conditions such as spill fires of fossil fuel during a traffic incident. Low intensity fires, e.g., smouldering fires, which can hardly trigger TPRD sensing element, are beyond the scope of this study yet must be addressed by GTR#13 fire test protocol too.

Overview of microleaks-no-burst (μLNB) safety technology

Fig. 3 schematically explains the performance of a standard (left) and a μLNB tank (right) in a fire. The standard tank has a liner and a fibre reinforced polymer (FRP). The μLNB tank has, in addition, a thermal protection layer (TPL) that can be load-bearing as well. Heat flux from a fire is applied to the external tank surface. The common features for standard and μLNB tanks include the heat propagation into the wall and the degradation of resin in the composite ("Resin decomposition" line), as well as the moving outwards load-bearing wall thickness fraction ("Load bearing fraction" line). In the case of standard tank, when these two fronts, i.e., the resin decomposition front and the load-bearing wall thickness fraction location, meet each other the tank is not anymore able to bear the load of increasing in fire hydrogen pressure and ruptures. This happens for the standard tank because the hydrogen-tight liner does not melt before the rupture conditions are met.

The μLNB tank has two composites in the wall, one over another, of different thickness and properties, including thermal conductivity, heat of decomposition, etc. The self-venting performance of the tank is provided by a proper design using the intellectual property of Ulster University [6,7] and in-house proprietary models and tools [32,37] accounting for all important thermophysical and geometrical parameters of the liner, two composite layers, the safety factor that is the ratio of the tank initial burst pressure to the nominal working pressure, etc. The design of μLNB tank provides melting of the liner before the tank loses its load-bearing ability. The melting of liner initiates microleaks of hydrogen through structure of FRP and TPL layers which are not hydrogen-tight. Despite further propagation of the decomposition front into the tank wall (see Fig. 3, right), the load-bearing wall thickness fraction reduces drastically due to the tank depressurisation through the "natural" microchannels in the composites. This eliminates conditions for tank rupture in a fire and thus devastating blast wave, large fireball, and projectiles, including a vehicle itself.

The design of μLNB tank strongly depends on the choice of liner material and thickness. For example, higher melting temperature of Nylon, i.e. polyamide (PA), liner, e.g., 219 °C [39], compared to that of high density polyethylene (HDPE) liner, e.g., 118–134 °C [5,6] would result in a design with a thicker double-composite wall for a tank with PA liner. The HDPE liner takes much less amount of heat to melt it, than it would to melt the PA liner. There is another substantial safety advantage of HDPE compared to PA liner. Numerical experiments performed at Ulster University [7] have explained the interesting observation in the previous experimental campaigns [20,21], where Type IV composite tanks with HDPE liner leaked in a fire without rupture if they were charged with pressures below of about the half of the nominal working pressure (NWP). This would not be possible for PA liner. In addition, PA mechanical properties are less favourable compared to HDPE liner at temperatures below −40 °C, which may be important for use of hydrogen storage, e.g., for high altitude aviation applications, etc.

The experimental studies by Ruban et al. [21]. and Blanc-Vannet et al. [20]. demonstrated the leakages of Type IV hydrogen tanks in fires at lower states of charge (SoC) due to the melted liner. This phenomenon was reproduced in simulations by the authors [25] and explained. The fires in experiments were continuous. No research was found on the interrupted fire test with hydrogen tank where the burner would be terminated, and/or with flame extinction. Therefore, there is a knowledge gap on the Type IV hydrogen tanks behaviour in such conditions that should be investigated and closed.

The significant not related to the safety benefit of the μLNB technology is the reduction of amount of shortage in supply of carbon fibre [40,41] and substitution of at least a part of it by cheaper (in some cases the prices differ by the order of magnitude) fibres like glass, basalt, etc. This, along with the increase of public confidence in safety of hydrogen systems and infrastructure, will accelerate the transition to the economy based on the use of renewable electricity and green hydrogen.

The approach applied by HySAFER to design and manufacture μLNB tank prototypes is based on the use of a standard tank design as a starting point. This allows tank manufacturers in most cases to use their usual design of liner and bosses as well as the way of filament winding. This facilitates manufacturing of inherently safer hydrogen storage tanks by the collaborators around the globe using their facilities, established procedures and acquire a strong competitive advantage on the market due to unprecedented safety features of μLNB tanks.

Characteristics of tank prototypes and testing procedure

Hydrogen storage tank rupture during a fire incident is a critical concern for the responders at an incident scene. In this study we expand the validation domain for this innovative safety technology of explosion free in fire self-venting (TPRD-less) tanks from scenarios of continuous fire [6] to scenarios of intervention at the fire scene. This is relevant to intervention of responders not only to fires involving hydrogen vehicles on roads, but equally to fires in storage rooms on hydrogen-powered trains, maritime vessels in harbours, planes at

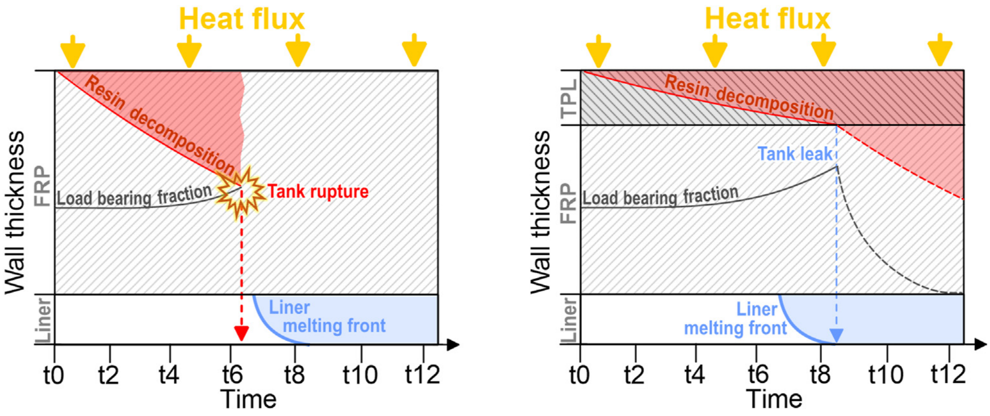

Fig. 3 – Schematic explanation of the μLNB safety technology performance in a fire: original tank (left) vs μLNB tank [6] (right).

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Table 1 – Parameters of the six μLNB tank prototypes of 7.5 L and NWP = 70 MPa tested in fire intervention conditions.

Prototype	Liner	Layer 1	Layer 2	Outside D increase*	Fire scenario
COPV#CC	L1	CFRP#1	CFRP#2	2%	Removal from a fire
COPV#CB-1	L1	CFRP#1	BFRP	2%	Removal from a fire
COPV#CB-2	L2	CFRP#1	BFRP	0%	Water supply to fire
COPV#CB-3	L1	CFRP#1	BFRP	0%	Water supply to fire
COPV#CB-4	L2	CFRP#1	BFRP	2%	Water supply to fire
COPV#CB-5	L2	CFRP#1	BFRP	0%	Water supply to fire

Note: * - increase of diameter compared to the original standard tank.

airports, etc. To address the safety concerns of firefighters, all fire tests were performed following regulations UN GTR#13 and EC R134 [31,42]. The localised and engulfing sections of the burners provided the specific heat release rate of HRR/A = 1 MW/m^2 characteristic for realistic gasoline/diesel spill fires rather than fires with decreased HRR/A as per the GTR#13 (Phase 2) fire test protocol of 0.3 MW/m^2 and 0.7 MW/m^2 respectively [26,28].

Table 1 shows the parameters of six μLNB tank prototypes tested in two different fire intervention scenarios within the research programme of the HyTunnel-CS (https://hytunnel.net/) project coordinated by Ulster University. The HySAFER Centre of Ulster University designed all μLNB tanks using in-house heat and mass transfer models with phase transitions (degradation and melting) [32,37]. Our USA collaborator manufactured the tank prototypes. The designs of the prototypes were based on the original 7.5 L and NWP = 70 MPa Type IV tanks, with HDPE liners and of sizes 186 × 520 mm (L/D = 2.8). The HyTunnel-CS project partner French Alternative Energies and Atomic Energy Commission (CEA) performed fire tests analysed in this study for the scenario with tank removal from the fire (two first tank prototypes COPV#CC and COPV#CB-1, Table 1). The HyTunnel-CS project partner University of South-Eastern Norway (USN) conducted tests for the scenario of fire extinction by water spray (test with tank COPV#CB-5), and the fire testing laboratory in the USA investigated the same scenario in tests with three tanks (COPV#CB-2 to COPV#CB-4).

Two grades of HDPE liner (L1, L2), two carbon fibre reinforced polymers (CFRP#1, CFRP#2), and one basalt fibre reinforced polymer (BFRP) as a thermal protection layer (TPL) were used to design and manufacture the tank prototypes. The first two tanks in Table 1 were tested in the scenario of removal of the tank from a fire. The behaviours of other four tanks were evaluated in fire tests with extinction conditions using water sprays. Both scenarios were imitating intervention by firefighters at the fire incident scene involving hydrogen vehicle. The first two and the fifth μLNB tank had outside diameter slightly increased compared to the original standard tank diameter by 2%. Other three μLNB prototypes had external diameter exactly as in the original standard tank (requires protection by TPRD with all mentioned above drawbacks). The μLNB tanks generally have a diameter equal or with minimum deviation from the original tank diameter, and the portion of the original carbon fibre composite wall is substituted by a composite with different, a cheaper fibre. This means that μLNB tanks will have equivalent and, in some cases, provide savings in material costs, compared to the standard Type IV tank (which do explode in a localised fire or in engulfing fire, in case a TPRD is not triggered, triggered with unacceptably long delay or is faulty).

Results and discussion: removal from a fire and fire Re-ignition

Fig. 4 (left) shows the pressure and temperature dynamics in the μLNB tank made of carbon-carbon double-composite wall (COPV#CC) during the fire test. Fig. 4 (right) presents the pressure and temperature transients for carbon-basalt double-composite wall tank (COPV#CB-1) during the fire test of the same intensity of realistic fire of HRR/A = 1 MW/m^2. Both tanks undergone the same testing procedure. Pressure and temperature transients inside the tanks demonstrated similar

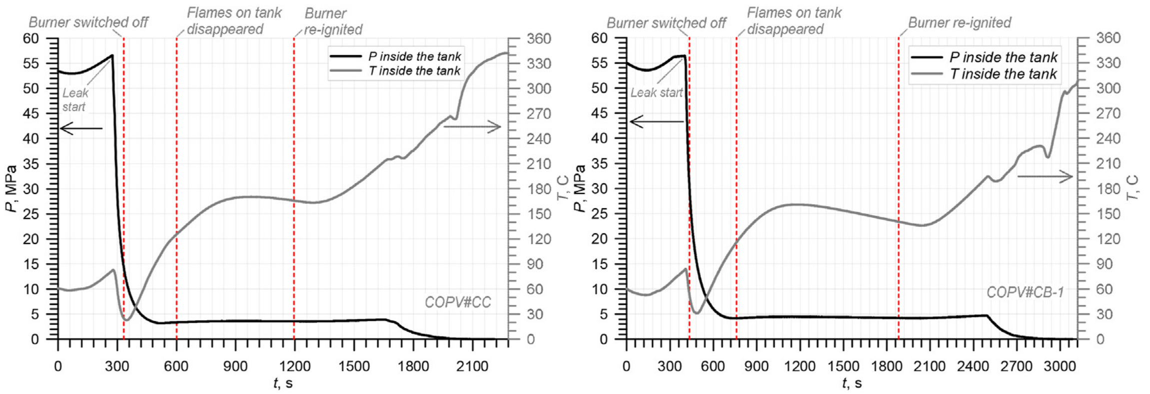

Fig. 4 – Pressure and temperature transients in μLNB tanks with liner of grade L1 during the fire test. Left: carbon-carbon double-composite wall tank COPV#CC. Right: carbon-basalt double-composite wall tank COPV#CB-1.

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tendencies with few differences. The initial pressure in both tests of CEA in real tunnel was 54–55 MPa, i.e., below the NWP = 70 MPa. In the fire, pressure and temperature inside the tank grow due to heat transfer through the wall from the external fire. In the case of carbon-carbon (COPV#CC) μLNB tank, hydrogen release through the microchannels of the composite wall started at about 4 min 40 s, and for the carbon-basalt (COPV#CB) tank later at 6 min 40 s. The microleaks are manifested by a sharp pressure drop from 56 to 57 MPa to about 15 MPa in just a minute. During this short time of pressure drop, the hydrogen temperature inside the tank decreased from about 80 °C to 24 °C for the COPV#CC tank and to 29 °C for the COPV#CB tank due to gas expansion. To imitate the removal of vehicle located over a spill fire, the burner was switched off (left vertical dashed line on the graphs) when the hydrogen release started (following the melting of liner in the μLNB tank).

Because combustion of the resin of the composite continues after the burner was switched off, hydrogen temperature in tanks was growing further. Hydrogen temperature continued to grow even after the visible flames disappeared on the tank surface (middle vertical dashed line) at 10 min for the COPV#CC prototype and 12 m 40 s for the COPV#CB-1 tank (invisible microflames could still be present [43]). Because of heat accumulated in the wall and its higher temperature, hydrogen temperature continued to raise for about 6 more minutes for both tanks. Only then hydrogen temperature began to decrease. The pressure decrease stopped at about 8 min for the COPV#CC tank and 12 min for the COPV#CB-1 tank when the pressure in both tanks stabilised at 3.5–4.3 MPa pressure plateau. Such residual pressure of 4.3 MPa would require more than 33 times (NWP = 70 MPa multiplied by safety factor 2.25 and divided by 4.3 MPa) thinner wall compared to the initial wall thickness to bear the load. This could be equivalent of one composite ply, if tanks original wall thickness would be 33 mm. The decreased pressure inside the tank seems was not able to initiate microleaks in the absence of external fire even if the temperature of hydrogen measured by the thermocouple reached 160–170 °C, i.e., above the liner melting temperature. This can be explained by the extreme contraction of the composite due to the abrupt pressure drop and therefore, tightening the microchannels and terminating the leak. Due to the follow-on heat transfer from the re-initiated fire, the resin of the remained load-bearing virgin composite continued to decompose and hence, to form more micro-channels. This resulted in a later secondary leak and drop of inner pressure to atmospheric.

To complicate the intervention scenario, it was assumed that the fire re-ignites. To imitate this, the burner was re-ignited in the experiment (right vertical dashed line on the graphs of Fig. 4). The COPV#CC tank started to leak again after 7 min 30 s from re-ignition, and the microleaks in the COPV#CB-1 tank began with 10 min 30 s delay after re-ignition. Hydrogen temperature reached at the time of the second leak about 210 °C in the COPV#CC tank and about 195 °C in the COPV#CB-1 tank. Only at this comparatively elevated temperature of hydrogen, which is above the melting temperature of liner, in the combination with reduced significantly below NWP pressure, can re-start microleaks. The second initiation of microleaks is manifested by a slight temperature drop due to gas expansion. Finally, the pressure drops to atmospheric in 5 min after the re-start of the microleaks for both tanks. Yet, the hydrogen temperature continues to grow due to heat from the fire even there is no overpressure in the tank. Thermocouple readings reach about 340 °C for the COPV#CC tank and 310 °C for the COPV#CB-1 tank at the end of the measurements. This is close to epoxy resin decomposition temperature of about 280–375 °C in the composite, e.g. Ref. [11], but significantly below the decomposition temperature of carbon fibres of about 700–750 °C for carbon fibres [44]. The increase of temperature after the pressure in the tank dropped to atmospheric could be explained, e.g., by the contact of thermocouple with melted liner or resin, or by penetration of hot combustion products inside the tank.

Fig. 5 shows a series of snapshots of fire test with COPV#CB-1 prototype. The test starts when the burner is ignited (snapshot "0 s"). Microleaks are started after the liner melting at 6 min 40 s (snapshot "6 min 40 s"). The flame size around the tank is the same with insignificant increase at the moment of leak start. Snapshot "7 min 20 s" shows combustion of resin of the tank when the burner is switched off. What is seen in this snapshot is the combustion of composite resin assisted by hydrogen released through the microchannels in the wall. This hydrogen-assisted resin combustion is seen almost a minute after, in snapshot "8 min 30 s", where the flames got smaller. Few residual flames only are seen in snapshot "11 min 40 s" that corresponds to the time when pressure drop stops due to the contraction of the composite wall at significantly decreased pressure and formation of the pressure plateau at level of 4.3 MPa, as well as freezing of melted before liner. No flame observed at snapshot "13 min 20 s".

Results and discussion: fire extinction

Fig. 6 shows comparison of pressure and temperature dynamics for tank COPV#CB-2 (left) and tank COPV#CB-3 (right) for scenario with water jets supply to the tank from the above. The only difference in tanks' design is the grade of liner. The order of actions in the tests was as follows. The burner was ignited when pressure in tanks was equal to NWP = 70 MPa. Tank COPV#CB-2 started to leak after melting of liner L2 after 4 min 45 s when pressure inside the tank increased to 78 MPa, while liner L1 in COPV#CB-3 melted faster at 3 min 50 s when pressure raised to only 74.5 MPa. The rate of pressure growth was the same in both tanks but in test COPV#CB-3 liner L1 melted earlier. The drop of pressure in the test with tank COPV#CB-2 is responsible for the decrease of hydrogen temperature from 45 °C down to −38 °C (decrease by 83°), while the smaller rate of pressure decrease in tank COPV#CB-3 resulted in temperature decrease from 62 °C to minimum of 26 °C (decrease by 36° only).

In about 10 s after the start of microleaks the sprinkler was switched on and water sprays were applied to the top to the burning tank surface. Then in 10–20 s the burner was switched off. Then the two tests proceeded differently. While in the test with tank COPV#CB-2 the water supply continued to the test end, in the test with tank COPV#CB-3 the water supply

Fig. 5 – Snapshots of the μLNB tank fire test with COPV#CB-1.

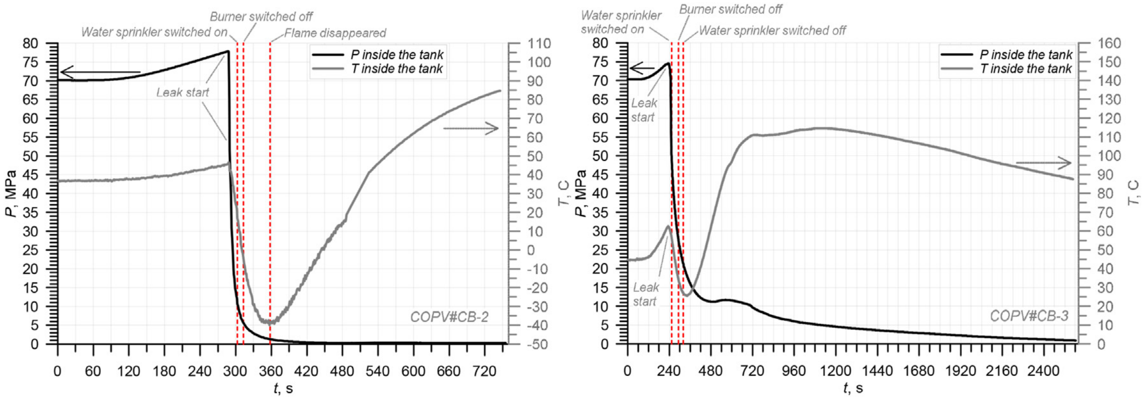

Fig. 6 – Pressure and temperature transients measured inside μLNB tank prototypes during the fire tests: COPV#CB-2 with liner L2 (left), COPV#CB-3 with liner L1 (right).

was switched off in 20 s after the burner was switched off. This is thought to be a reason of larger temperature drop in test with COPV#CB-2. The visible flames on the tank surface disappeared in both of these tests.

Fig. 7 shows the pressure and temperature dynamics inside μLNB tank prototypes COPV#CB-4 (left) and COPV#CB-5 (right) during the fire tests performed in different laboratories. Both tanks had liner L2 and the external diameter of tank COPV#CB-4 was slightly (2%) larger than in the original standard tank and other prototypes.

Fig. 8 presents snapshots explaining the development of the fire test with μLNB tank prototype COPV#CB-5. The test begins from the localised fire stage of intensity HRR/A = 1 MW/m^2 (snapshot “0 s”). Resin combustion is seen in snapshot “1 min 19 s”. The hydrogen starts to leak through microchannels in the wall after the liner melted at 5 min 30 s (not shown in Fig. 8). The burner was switched off shortly after the microleaks began. The epoxy resin of the composite continues to burn afterwards (see snapshot “5 min 49 s”). Then, the sprinkler is switched on to supply water jets on the top of the tank (snapshot “5 min 55 s”). The direction and moderate intensity of water supply is not sufficient to fully terminate combustion, which is seen on the bottom surface of the tank (snapshot “6 min 30 s”). When the sprinkler was stopped the video allows to resolve weak flames (see snapshot “13 min 30 s”) beneath the tank. The pressure of hydrogen in the tank dropped to atmospheric at 16 min.

The analysis of temperature transient in Fig. 7 (right) shows that the initial hydrogen temperature in the tank was 43 °C (probably above the ambient due to insufficient time for colling after filling the tank by hydrogen), and then went up to 76 °C before the microleaks started, then dropped to the minimum of 32 °C (by 44°) due to the gas expansion during pressure relief through microleaks. Then temperature started to grow again even in the presence of water supply on the tank top. However, the residual combustion at the bottom of the tank visible in the video seems was sufficient to provide temperature increase from 32 °C up to the maximum of about 57 °C at time 12 min 30 s. The combustion at the tank bottom could be hydrogen assisted resin combustion that

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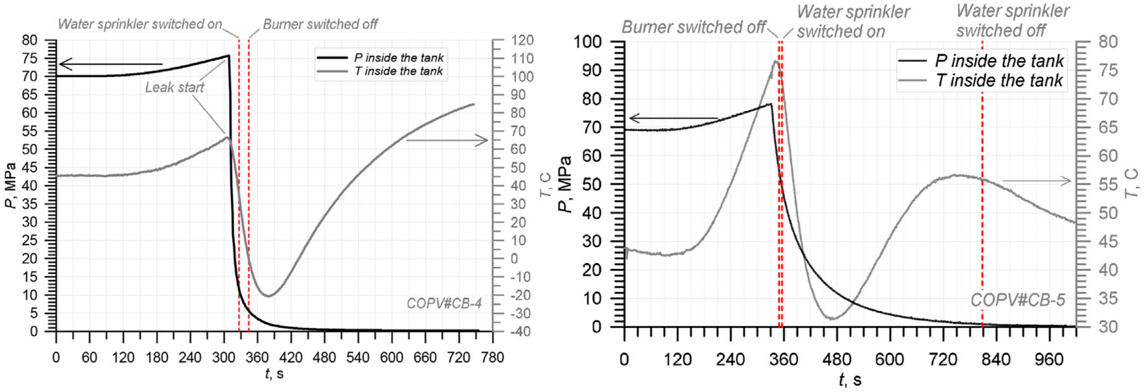

Fig. 7 — Pressure and temperature transients inside μLNB tank prototypes during the fire tests: COPV#CB-4 (left) and COPV#CB-5 (right) both with liner L2.

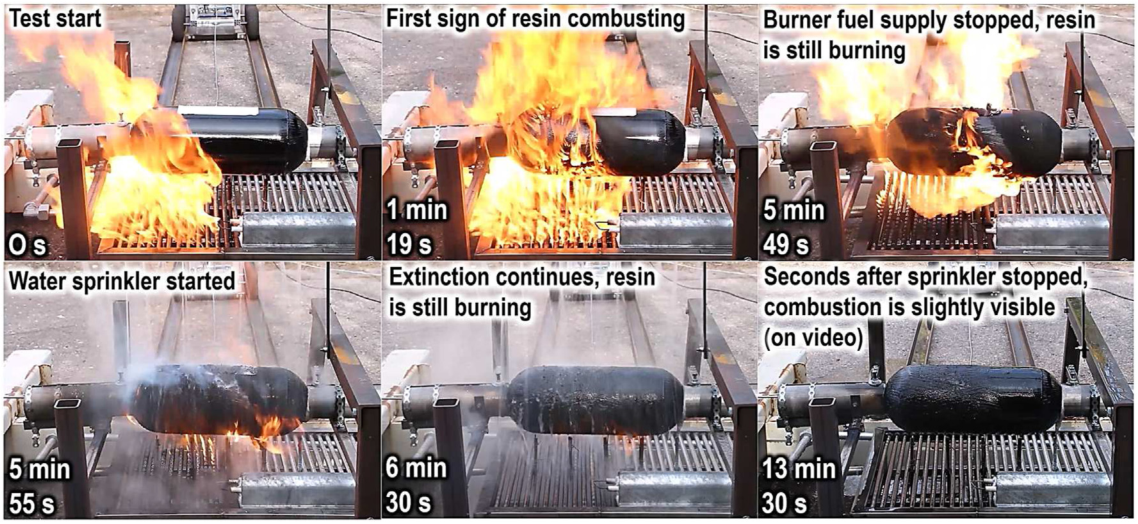

Fig. 8 — Snapshots of the μLNB tank prototype COPV#CB-5 behaviour in the fire test.

ceases when the pressure at the tank tends to atmospheric. This explains temperature decrease after 12 min 30 s of the test.

Hydrogen temperature in the test with tank COPV#CB-4 (Fig. 7, left) grows after the pressure in the tank drops to atmospheric. Like for tests with COPV#CC and COPV#CB-1, it could be explained by the contact of the thermocouple in the tank with melted and deformed liner or resin, or penetration of hot fire products through the matrix of fibres with degraded resin.

Tests with COPV#CB-4 and COPV#CB-5 (both with HDPE liner of grade L2) support the observation made from the test with COPV#CB-2 analysis that the use of grade L2 liner can eliminate the existence of the pressure plateau at all, and provide faster release of hydrogen (pressure drop in the tank to atmospheric took in tanks with liner L2 from 8 min (COPV#CB-2, COPV#CB-4) to maximum 16 min (COPV#CB-5) and it takes more than 43 min for tank COPV#CB-3 with liner L1. However, it is worth noting that faster release of hydrogen could require large vent area for mitigation of the pressure peaking phenomenon [45–49] in confined space of hydrogen storage rooms and adequate natural ventilation.

Conclusions

The *originality* of this study is in the investigation of explosion free in fire self-venting (TPRD-less) tank performance beyond the fire test protocol of GTR#13 (Phase 2), i.e., in realistic conditions of fire intensity of $HRR/A = 1\ MW/m^2$ characteristic for gasoline/diesel spill fires, with imitation of different intervention strategies of responders to extinguish the fire. The scenario of a hydrogen vehicle with onboard storage tank removal from the fire scene with re-ignition, and scenarios of continuous and temporary extinction of the fire by water supply on the tank were investigated. The study revealed that the proper choice of HDPE liner grade could further improve the performance of the technology and eliminate the low-pressure plateau.

The *significance* of this work is in the demonstration that self-venting μLNB tanks could have the same size as original tanks but exclude rupture in a fire, including conditions of intervention of responders at a fire scene. The use of μLNB tanks reduces hazards and associated risks for first responders when dealing with fires of hydrogen-powered

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transport and fires in storage enclosures onboard of road vehicles, trains, marine vessels, planes at airports and hydrogen storage infrastructure at hydrogen refuelling stations. The same is valid for the fire fighting in confined spaces like tunnels, underground parking, etc. The design of explosion free in a fire TPRD-less tank usually reduces the use of carbon fibres, as being seen in high demand and with almost doubled costs during last years, by cheaper ones. It is found that for the scenario of hydrogen storage tank removal from the fire, the microleaks through the composite wall could cease due to contraction of the wall or solidification of liner. This occurs after the reduction of pressure in the tank by the order of magnitude and accompanied by solidification of previously melted liner during temperature drop as the result of gas expansion. The tank does not rupture with the residual plateaued pressure inside, because, despite the resin decomposition to the wall depth, the decomposition of fibres does not happen due to the higher decomposition temperature. Thus, hydrogen will rather leak than the tank shell with degraded resin will lose structural integrity. This is proved by the extension of the removal scenario to re-ignition of fire under the tank that resulted in the safe secondary release of hydrogen in the form of microleaks and pressure drop in the tank to atmospheric. Testing of μLNB tanks in these scenarios confirmed that the fire extinction does not interrupt hydrogen release through microleaks, i.e., firefighters can conduct their interventions at an incident scene following current strategies and tactics. The standard firefighting procedures could be followed as the use of μLNB self-venting tanks eliminates hazards of blast waves, fireballs, projectiles, long flames from TPRD, formation of flammable cloud and hot products under the ceiling of underground parking, mitigates the pressure peaking phenomenon in enclosures, reduces property loss, and protects life from adverse effects of incidents involving hydrogen.

The *rigour* of this study is confirmed by experimental validations of the μLNB technology efficiency for 6 tank prototypes of 7.5 L volume and NWP = 70 MPa made of carbon-carbon (1 tank) and carbon-basalt (5 tanks) double-composite walls prototypes in conditions of fire intervention. The μLNB tanks are tested at realistic fire intensity of HRR/A = 1 MW/m^2, which is above those dangerously reduced by the GTR#13 (Phase 2) fire test protocol, and conditions imitating different scenarios of first responders' intervention at the fire scene. All tank prototypes successfully passed fire testing in scenarios with intervention by tank removal and water jets supply on the tank surface.

The breakthrough safety technology of explosion free in fire self-venting (TPRD-less) tank opens the way for tank and vehicle manufacturers to drastically reduce the hazards and associated risk of hydrogen-powered vehicles to the acceptable level of life safety and property protection, including safety of first responders. The paper described in detail the performance of μLNB tank prototypes and the technology validations in conditions imitating the intervention of responders at the fire incident scene with involvement of hydrogen-fuelled vehicle. However, some proprietary information is not disclosed being the intellectual property of Ulster University.

Disclaimer

Funded by the European Union. 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.

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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