TOWARDS FIRE TEST PROTOCOL FOR HYDROGEN STORAGE TANKS

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ABSTRACT

The reproducibility of fire test protocol in the UN Global Technical Regulation on Hydrogen and Fuel Cell Vehicles (GTR#13) is not satisfactory. Results differ from laboratory to laboratory and even at the same laboratory, when fires of different heat release (HRR) rate are applied. This is of special importance for fire test of tank without thermally activated pressure relief devise (TPRD), the test requested by firemen. Previously the authors demonstrated a strong dependence of tank fire resistance rating (FRR), i.e. time from fire test initiation to moment of tank rupture, on the HRR in a fire. The HRR for complete combustion at the open is a product of heat of combustion and flow rate of a fuel, i.e. easy to control in test parameter. It correlates with heat flux to the tank from a fire – the higher HRR the higher heat flux. The control of only temperature underneath a tank in fire test, as per the current fire test protocol of UN GTR#13, without controlling HRR of fire source is a reason of poor fire test reproducibility. Indeed, a candle flame can easily provide a required by the protocol temperature in points of control, but such test arrangements could never lead to tank rupture due to fast heat dissipation from such tiny fire source, i.e. insufficient and very localised heat flux to the tank. Fire science requires knowledge of heat flux along with the temperature to characterise fire dynamics. In our study published in 2018 the HRR is suggested as an easy to control parameter to ensure the fire test reproducibility. This study demonstrates that the use of specific heat release rate, HRR/A, i.e. HRR in a fire source divided by the area of the burner projection, A, enables testing laboratories to change freely a burner size depending on a tank size without affecting fire test reproducibility. The invariance of FRR at its minimum level with increase of HRR/A above 1 MW/m^2 has been discovered first numerically and then confirmed by experiments with different burners and fuels. The validation of computational fluid dynamics (CFD) model against the fire test data is presented. The numerical experiments with localised fires under a vehicle with different HRR/A are performed to understand the necessity of the localised fire test protocol. The understanding of fire test underlying physics will underpin the development of protocol providing test reproducibility.

KEYWORDS: hydrogen, alternative fuel, onboard storage, fire test, fire resistance rating, heat release rate.

ABBREVIATIONS

CFD	Computational Fluid Dynamics	FRR	Fire Resistance Rating
CFRP	Carbon Fibre Reinforced Polymer	GTR	Global Technical Regulation
CGH2	Compressed Gaseous Hydrogen	HRR	Heat Release Rate
CNG	Compressed Natural Gas	LES	Large Eddy Simulation
CV	Control Volume	OEM	Original Equipment Manufacturer
DO	Discrete Ordinates	TC	Thermocouple
FCV	Fuel Cell Vehicle	TPRD	Thermally-activated Pressure Relief Device

1.0 INTRODUCTION

The fuel cell vehicles (FCVs) with zero emission are already on roads with compressed gaseous hydrogen (CGH2) stored onboard in composite tanks at nominal working pressure up to 70 MPa. There are about 5500 FCVs in California (USA) and 2800 FCVs in Japan [1]. Hydrogen refuelling stations for FCV operate at even higher pressures, i.e. up to 100 MPa; number of stations worldwide is growing, e.g. there are 62 in Germany, 40 in California, 100 in Japan [1]. Composite cylinders for CGH2 with plastic liner (Type IV) for the gas tightness are selected by major original equipment manufacturers (OEMs) due to lightweight and high strength to provide competitive driving range. Safety of the hydrogen storage cylinders is the key challenge to hydrogen-powered vehicles and refuelling infrastructure. The fire resistance rating (FRR), i.e. time of tank in a fire before rupture in the case thermally-activated pressure relief device (TPRD) does not operate, e.g. due to its blockage during an accident or non-zero failure probability, of currently used tanks is only 4-16 minutes [2] , [3]–[5]. Severe blast wave, fireball, and projectiles are catastrophic consequences of a hydrogen storage tank rupture in fire in the open [6]–[8]. In confined space like garage the release of hydrogen can demolish civil structure by the pressure peaking phenomenon revealed at Ulster in 2010. It is yet unclear what hydrogen inventory, in case of tank rupture in a fire, would be allowed for hydrogen vehicles in tunnels. This is being addressed in HyTunnel-CS project funded by FCH JU and started on the 1st of March 2019 and coordinated by Ulster University. These are serious public safety concerns that OEMs must address and are working on. Even compressed natural gas (CNG) vehicles related accidents associated with ruptures of cylinders reported recently have demonstrated quite devastating consequences [9], [10]. Half of CNG tanks rupture are due to fire and failure of TPRD to activate. Thus, understanding of high-pressure tank behaviour in a fire is important. Fire test should be devised not only to pass the standardised procedure as a part of type-approval of a vehicle but be reproducible in different laboratories and provide enough information on tank behaviour in actual vehicle fires as close to reality as possible.

The HySAFER research on quantitative risk assessment (QRA) of onboard CGH2 storage is probably the only one published in peer reviewed literature [11]. This QRA research demonstrated that the risk of FCH vehicles on London roads, including data on published elsewhere failure probability of TPRD, is acceptable only when FRR of hydrogen onboard storage tanks is above 45 minutes. This is significantly above FRR on currently used onboard storage tanks. There are different means to increase FRR, e.g. insulation blankets, protection shell, intumescent paint, recent explosion-free in fire safety technology, etc. The FRR increase up to 2 hours, which is comparable with the car fire duration [12], has been demonstrated recently using intumescent paint [3]. The patented breakthrough leak-no-burst (LNB) safety technology [13], which is being developed at Ulster University, excludes tank rupture in fire and results in insignificant leakage of hydrogen though tank composite wall after melting a liner. The insignificant leak flow rate is equivalent to flow rate through an orifice diameter of only fractions of millimetre. Due to the insignificant distributed leak, this engineering solution excludes long flames and the pressure peaking phenomenon (PPP), i.e. the phenomenon which is unique only for hydrogen when it leaks inside the enclosure like garage or maintenance shop [14]–[16].

The UN Global Technical Regulation on Hydrogen and Fuel Cell Vehicles No. 13 (GTR#13) [17] and Regulation No. 134 (R134) [18] specify the current procedure for testing the service terminating performance of a CGH2 storage system in a fire. The existing regulation does not address the FRR of a hydrogen tank, which is required by first responders as they need to know time to tank rupture for development of their intervention strategy and tactics at accident scene. Educational training for first responders within European HyResponse project (www.hyresponse.eu) underlines the importance of information on FRR and availability of tools for assessment of hazards after tank rupture in fire [19]. The regulated fire test aims to demonstrate the performance of a system of storage tank and TPRD in a fire. The test is successful if, following the fire test protocol, hydrogen is vented through TPRD without tank rupture. The only parameter controlled during the fire test is temperature of combustion products produced by a burner in defined locations beneath the tank. The authors cannot accept this test procedure, which is the main reason for poor test reproducibility in their opinion.

Indeed, following fire safety science knowledge, the study [2] confirmed that not only control of temperatures under the cylinder (as required by GTR#13 and R134 test protocol), but also the burner heat release rate (HRR) strongly affects the FRR and thus can “assist” in passing, e.g. the localised fire test at comparatively low HRR and bring tank to rupture in a fire at higher HRR, which are characteristic for gasoline fires. It was found in [2] that FRR becomes reproducible, i.e. practically doesn’t change, when the “saturation” of the FRR is achieved at HRR>350 kW. However, the effect of burner size and tank size was not yet addressed in study [2].

It is suggested to relax the fixed burner dimensions in GTR#13 fire test protocol to enable testing cylinders of any size by adjusting burner size to tank size [2]. To improve the fire test reproducibility and make the test indeed “universal” for variety of tank sizes, it is proposed in this study to fix not simply HRR but the specific heat release rate, HRR/A, where A is the burner area. This changes the FRR saturation correlation curve proposed in [2] to that in Figure 1.

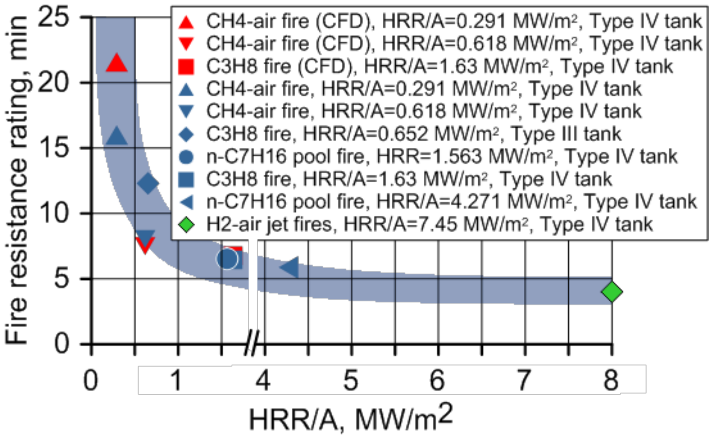

Figure 1. Dependence of FRR on burner’s HRR/A: CFD and experimental data [3]–[5], [20]–[22].

Figure 1 shows that for different cylinders, different fuels and burners types, the dependence of FRR with increase of HRR/A saturates at HRR/A>1 MW/m^2. It is worth to mention that HRR/A for gasoline spill fires is reported in literature as 1-2 MW/m^2. The use of burners with HRR/A of about 0.2-0.3 MW/m^2 will provide FRR of about 20 minutes (see Figure 1). The same tank tested at characteristic for gasoline fires HRR/A=1-2 MW/m^2 would have FRR of about 6 min only. This means that only localised fire test carried out at HRR/A=0.2-0.5 MW/m^2 can be successful because duration of localised portion of fire test is established as 10 min and FRR is above this time for such HRR/A. However, the test with realistic HRR/A>1 MW/m^2 in fire source could finish up by tank rupture if its FRR is below 10 min. There is a temptation (conscious or unconscious) to suggest a fire test protocol with lower HRR/A in fire source to pass the test for tanks with low fire resistance rating. This could be attempted in different ways, e.g. by adding requirement limiting flame height, etc.

One of key questions to answer during the development of fire test protocol is “What are HHR/A in automobile fires”. Although this information is well established and widely published in peer reviewed literature data, some developers interpret typical value of HRR/A in vehicle fire in their own way. The vehicle fire research over almost half a century (period from 1976 to 2017) demonstrates that HRR/A at a typical scenario of vehicle gasoline fire is accepted by professionals as: on road - HRR/A=2 MW/m^2 [23]; on road - HRR/A=2 MW/m^2 [24]; pool fire equation by Babrauskas for gasoline spill - HRR/A=2.2 MW/m^2 [25]; on concrete - HRR/A=0.8-1.0 MW/m^2 [26]. Ulster University proposes to perform fire test at representative value HRR/A≥1 MW/m^2 when FRR is practically constant.

The effect of wind at test site on stability and direction of burner flame at HRR/A>1 MW/m^2 is another issue to be addressed for a proper burner design. To provide the fire test reproducibility a wind should not affect requirements to minimum temperatures in points of control as required by GTR#13 and R134.

The approach of this study includes validation of CFD model against experimental data. Then the validated CFD model will be used to perform numerical experiments with other fire sources to draw conclusions on shaping reproducible fire test protocol.

2.0 ENGULFING FIRE: THE BLANKET BURNER

2.1 Experiment

The fire test series performed at Japanese Automobile Research Institute (JARI) were utilising the propane gas burner with the silica fibre cloth blanket applied for provision of the flame uniformity across the burner surface [27] (Figure 2, left). The total propane flow rate was $\dot{m}$=3 g/s ($\dot{V}$=100 NL/min). This produced the total HRR=0.137 MW. The blanket burner area was A=0.6 m^2 (LxW=1.2x0.5 m). Thus, the specific heat release rate was HRR/A=0.228 MW/m^2, i.e. below the threshold value of HRR/A=1 MW/m2 providing reproducibility of test and reflecting real life conditions.

The hydrogen tank was Type III tank (LxD=0.9x0.3 m) with 14 TCs covering the tank, 3 of them suspended at 25 mm under the tank and the rest were located on the tank exterior (Figure 2, right).

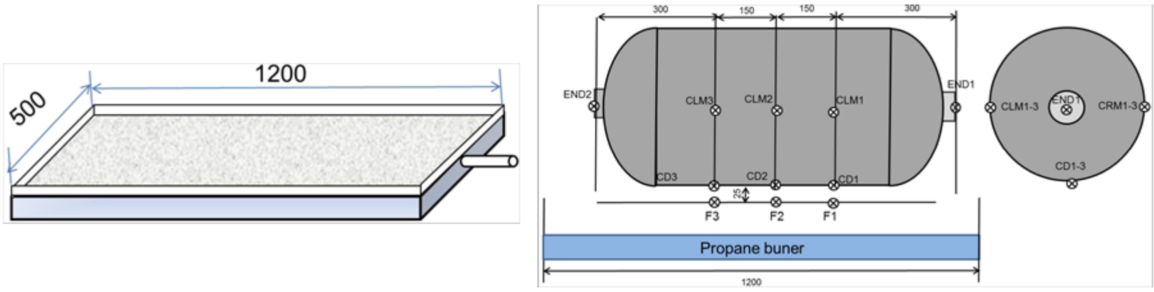

Figure 2. Blanket burner: burner sizes (left) and locations of TCs (right) [27].

2.2 Model description

The computational engine used for simulations of the fire tests was ANSYS Fluent. The 3D computational fluid dynamics (CFD) model solved the governing equations of conservation for mass, momentum, energy and species. The turbulence was simulated using Large Eddy Simulations (LES) with the Smagorinsky-Lilly sub-grid scale model [28]. The simulation of propane combustion and turbulence-chemistry interaction was performed using the Partially Premixed Combustion model of Fluent. It is based on the Non-Premixed Combustion model [29]. The soot formation was modelled using the advanced model for hydrocarbons Moss-Brookes [30]. The Discrete Ordinates (DO) [31], [32] radiation model was utilised for simulating radiative heat transfer. It suits well for combustion problems and covers the entire range of the flame optical thicknesses.

The simulation of the composite tank performance in a fire for calculation of FRR was performed as a separate problem formulation using "reduced" CFD model with the dynamically changed in time maximum heat flux adopted from the 3D CFD model simulations. The heat flux on a tank surface in 3D CFD simulation was adopted in the "reduced" model as the boundary condition on CFRP. In the reduced model the energy transport equation for solid body was solved, considering decomposition of the matrix in the composite wall due to the heat transferred from a fire. The model included the geometry of the transversal section of the tank wall (CFRP + liner) and hydrogen part with the length of the tank radius. In 3D CFD problem formulation the composite tank has non-uniform wall thickness in its different locations, e.g. cylindrical sidewall part (thicker) and dome part (thinner). The maximum heat flux value on composite in 3D numerical fire test, i.e. location on the composite wall where the degradation will bring the tank to failure faster, was identified and the corresponding wall thickness in this location was adopted in the "reduced" CFD model. The problem formulation for the "reduced" CFD model represents a "column" of control volumes arranged vertically (pie shape part of a tank), i.e. control volumes (CVs) of carbon fibre composite, CVs of liner and hydrogen. The CFRP and liner layers of the tank wall were meshed uniformly.

The original composite tank failure mechanism is applied in both, 3D and reduced CFD models [2]. The failure happens when spreading outwards "external" surface of the load bearing wall thickness (due to growth of pressure inside the tank during fire) meets propagating inwards resin degradation front.

The material properties of the tank implemented in the model are as follows. The CFRP thermal conductivity was k=0.4-0.6 W/m/K [33], specific heat capacity was c_p=1020 J/kg/K [34] and the density was ρ= 1360 kg/m^3 [33]. For the high density polyethylene (HDPE) liner (Type IV tank) thermal conductivity was k=0.2-0.4 W/m/K, specific heat capacity was c_p=2000-2600 J/kg/K and the density was ρ=940 kg/m^3 [35]. For the aluminium liner (Type III) thermal conductivity was k=202.4 W/m/K, specific heat capacity was c_p=871 J/kg/K and the density was ρ=2719 kg/m^3 [36].

The numerical meshes were built using ANSYS ICEM CFD. The geometry elements such as tank, hydrogen gas and ambient air were meshed separately and combined inside ANSYS Fluent solver using the mesh Interfaces feature. The meshes of hydrogen gas mesh and ambient gas, including fire sources, were designed using tetrahedral mesh, after that tetrahedral cells were converted to polyhedral cells in Fluent to optimize the number of cells and save computational time.

2.3 Problem formulation

In the numerical model, the fire source (blanket burner) was represented as in the experiment by a single surface of A=0.6 m^2 (LxW=1.2x0.5 m) releasing propane uniformly with specific heat release rate HRR/A=0.228 MW/m^2. The burner was positioned at 0.5 m above the ground (having the adiabatic wall boundary condition). The domain outer walls had pressure outlets boundary conditions. The ambient air temperature was 298.25 K as per experiment [27]. The calculation domain size was 15x15x15 m. The total number of the mesh CVs was 1.7M. The isometric views of the tank positioned above the burner and of the calculation domain with dimensions are given in Figure 3.

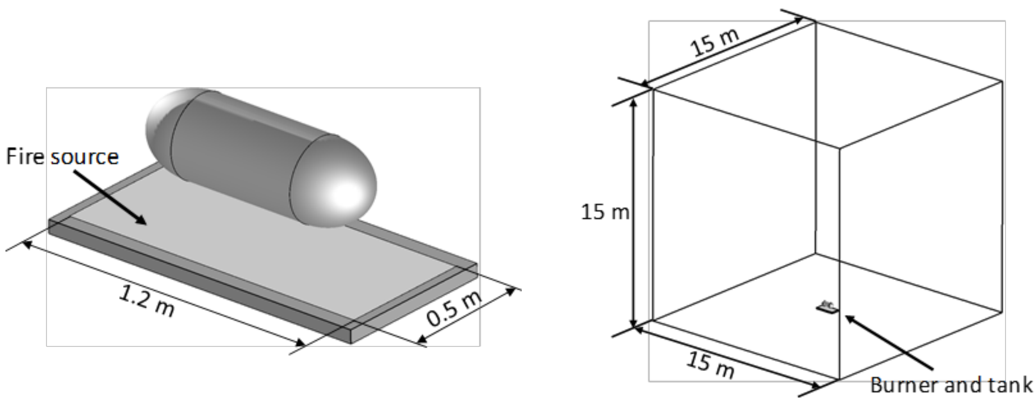

Figure 3. Blanket burner (left) and calculation domain sizes (right) [27] used in simulations.

2.4 Simulation results and comparison with experiment

Figure 4 shows that temperature in 3 locations 25 mm under the tank are reproduced by the CFD model with reasonable accuracy. The temperatures show fulfilment of the minimum temperature requirements of GTR#13 and R134 for the engulfing fire, i.e. 590°C (shown by horizontal line in Figure 4).

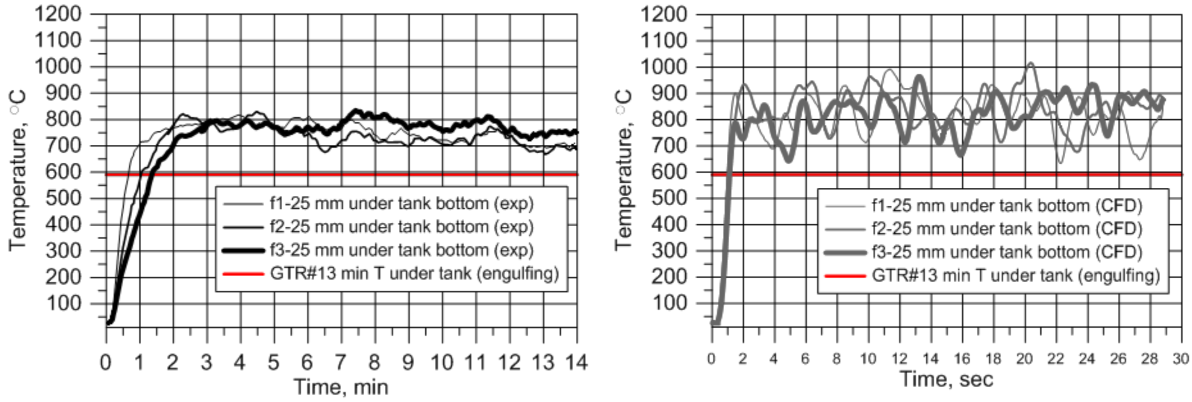

Figure 4. Engulfing fire test with blanket burner with HRR/A=0.228 MW/m^2: temperatures under the tank bottom at 25 mm (left - experiment [27]; right - CFD model, this study).

Figure 5 shows the experimental and simulated temperatures on the tank bottom (thermocouples CD1-3 in Figure 2, right). The established in simulations after initial period temperatures are about 10% higher compared to experimental temperatures, which is within acceptable engineering accuracy for such kind of tests.

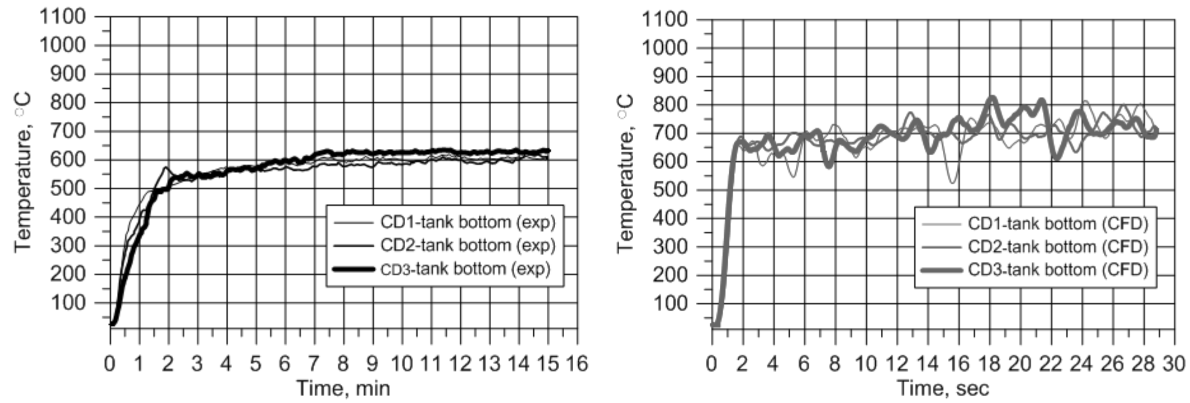

Figure 5. Engulfing fire test with blanket burner with HRR/A=0.228 MW/m^2: temperatures on the tank bottom (left - experiment [27]; right - CFD model, this study).

Figure 6 shows the experimental and numerically calculated temperature histories measured on the tank sides (thermocouples CLM1-3 and CRM1-3 in Figure 2, right). It should be noticed that simulations are performed only at initial stage until temperature stabilisation, which is shorter time compared to the experiment where inertia of thermocouple block affects the temperature dynamics at initial stage. The peaking of temperature at CL3 location in experiment is not clear to the authors.

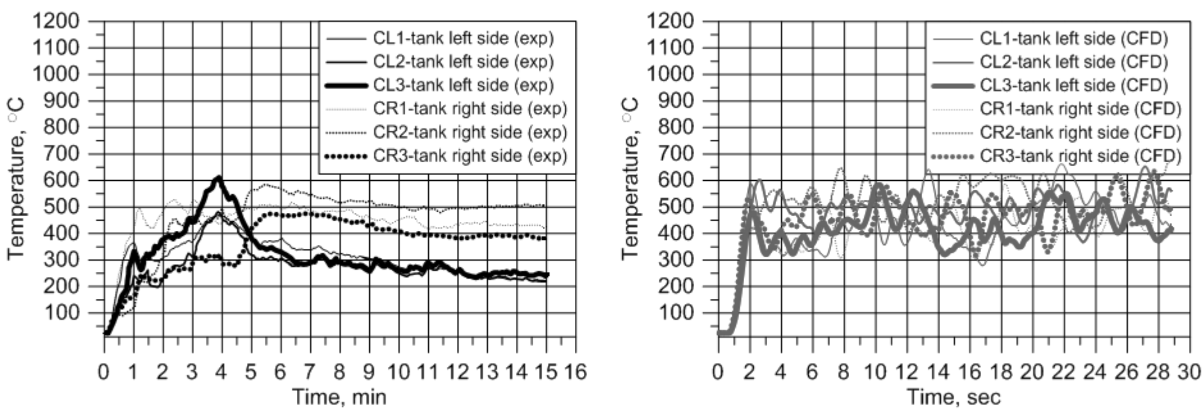

Figure 6. Engulfing fire test with blanket burner with HRR/A=0.228 MW/m^2: temperatures on the left and right sides of the tank (left - experiment [27]; right - CFD model, this study).

2.5 Simulation results: effect of HRR/A on FRR

To investigate the effect of the HRR/A on the heat flux to the tank and ultimately on FRR, the HRR/A was increased in simulations from 0.228 MW/m^2 to 1 MW/m^2. Hence, the flow rate of propane from the burner was increased in simulations from $\dot{m}$=3 g/s to $\dot{m}$=12.94 g/s. Figure 7 shows the numerical temperature transients at 25 mm under the tank at locations identical to previous simulations).

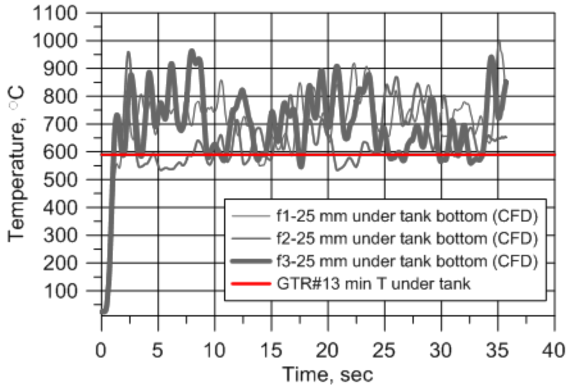

Figure 7. Engulfing fire test with blanket burner with HRR/A=1 MW/m^2: temperatures under the tank bottom at 25 mm.

In numerical test with blanket burner [27] and HRR/A=1 MW/m^2 the temperatures under the tank satisfy the minimum temperatures requirement of GTR#13 (and R134) for engulfing fire test (horizontal line in Figure 7). Thus, the blanket burner can be used for fire test corresponding to the reproducibility criterion and real automobile fire conditions (HRR>1 MW/m^2).

Figure 8 (left) compares the maximum heat fluxes on the tank in both numerical tests with blanket burner: HRR/A=0.228 MW/m^2 and HRR/A=1 MW/m^2. The FRRs for these two cases were calculated using the reduced CFD model implementing the dynamic heat flux over the time adopted from 3D simulations. The comparison of calculated FRRs is given in the graph (Figure 8, right) along with experimentally observed and reported in literature FRR values (Figure 8, right). It can be concluded that simulated data are within range of experimental data (blue strip). Both confirm the monotonic decrease of FRR with increase of HRR/A (see Table 1).

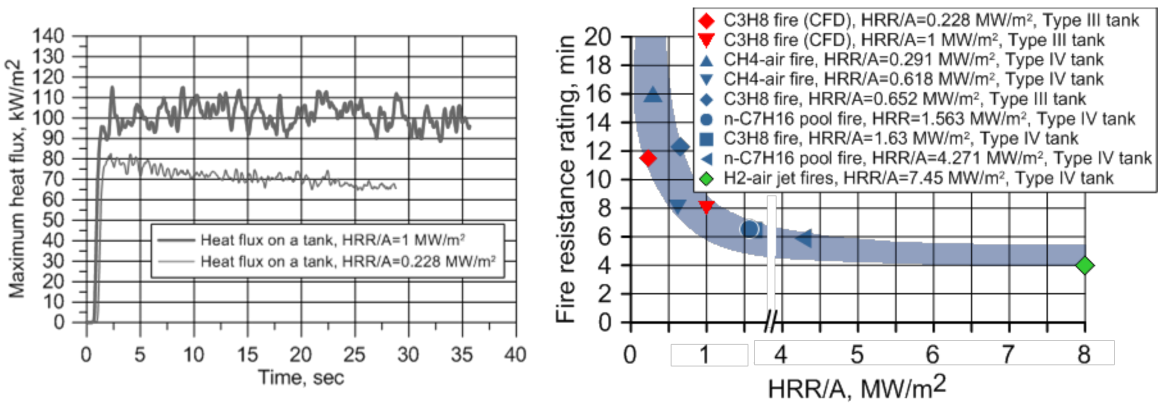

Figure 8. Engulfing fire tests with blanket burner. Left: maximum heat flux on tank (tests with HRR/A=1 MW/m^2 and HRR/A=0.228 MW/m^2). Right: numerical (two red symbols) and experimental [3]–[5], [20]–[22] data on FRR as a function of HRR/A.

Figure 8 (left) shows that the heat flux to the tank in test with HRR/A=1 MW/m^2 is about $\dot{q}''$=100 kW/m^2. It decreases significantly to $\dot{q}''$=65 kW/m^2 in test with HRR/A=0.228 MW/m^2. This difference in heat flux (due to different HRR/A) affects the FRRs obtained from simulations using the reduced CFD model by about 45%. It must be underlined that these results are obtained for no wind conditions.

Table 1. Details and results of engulfing fire numerical tests with the blanket burner.

Engulfing fire test	Heat flux on a tank at the beginning	FRR
HRR/A=0.228 MW/m^2	$\dot{q}''$=65 kW/m^2	11 min 30 s
HRR/A=1 MW/m^2	$\dot{q}''$=100 kW/m^2	8 min

2.6 Simulation results: wind 1.8 m/s

The effect of wind on blanket burner [27] performance was investigated in this study. The wind velocity of 1.8 m/s was applied in the simulations. This velocity was measured at testing location of Health and Safety Laboratory in Buxton (UK) during fire tests within EPSRC SUPERGEN Challenge project "Integrated safety strategies for onboard hydrogen storage systems" (EPSRC EP/K021109/1). In the fire test in Buxton the burner wind shield of 0.5 m height was used "to ensure uniform heating", as per GTR#13 and R134 requirements [17], [18].

The simulations with blanket burner had no shield to demonstrate the fire source performance in a light breeze wind of 1.8 m/s. The results have shown that the GTR#13 and R134 minimum temperature requirements were not satisfied: the temperatures under the tank were close to ambient 20°C. Thus, the blanket burner cannot provide the reproducibility of fire test under wind conditions (at least for wind velocities above 1.8 m/s). It could be used only in environment where wind is excluded, e.g. specialised closed facilities.

3.0 ENGULFING FIRE: THE PIPE BURNER

3.1 Problem formulation

The pipe burner is suggested in an attempt to combat the wind effect and thus to improve the fire test reproducibility in realistic field laboratory conditions. The 15 mm pipes arranged in parallel with 5 mm gaps in-between. Holes of 1 mm diameter formed in pipes for gas release are uniformly distributed at distances 20 mm in longitudinal and transversal directions. The burner is square shaped with the side length of 5 tank diameters (5x0.3 m=1.5 m in this case) producing the total area of A=2.25 m^2 with the 10 cm wind shield over the perimeter (Figure 9). The same tank as in the blanket burner simulations was used in this pipe burner case.

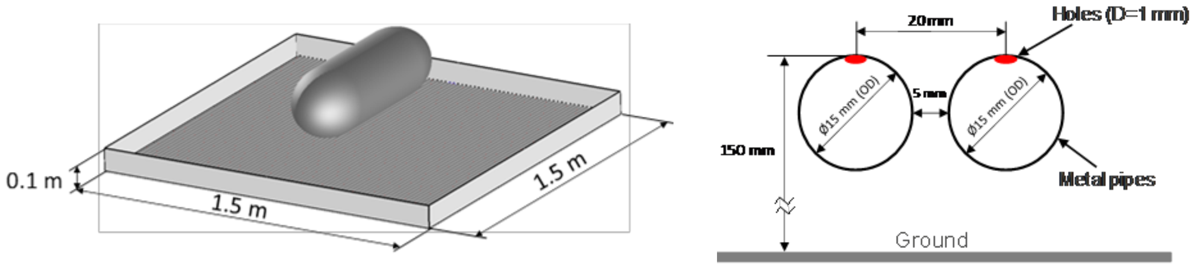

Figure 9. Dimensions of the pipe burner with the tank located above it (left) and dimensions of the pipes and holes and their positioning (right).

In the simulations the pipe burner was positioned at 0.15 m above the ground and the calculation domain size was 6x6x4 m. The total number of control volumes was 9.3M. Two simulations were performed with the same two HRR/A as for the blanket burner. Table 2 shows the details of these numerical tests.

Table 2. Details of engulfing fire tests with the pipe burner.

Case	Fuels and flow rates	Burner A	HRR	HRR/A
1	$C3H8\ \dot{m}$=11.07 g/s	2.25 m^2	0.513 MW	0.228 MW/m^2
2	$C3H8\ \dot{m}$=48.54 g/s	2.25 m^2	2.25 MW	1 MW/m^2

The additional benefit of the pipe burner compared to the blanket burner is that it provides the test reproducibility regardless of tank and burner size if five tank diameters size of burner is accepted (the scaling of burner size to tank size could be investigated further). The sizing should not affect the suggested minimum requirement HRR/A=1 MW/m^2.

3.2 Simulation results: no wind

Firstly, two engulfing fire tests with HRR/A as per Table 2 were simulated without wind to ensure the burner can reproduce the minimum temperature requirements of GTR#13 and R134 fire test protocol (Figure 10).

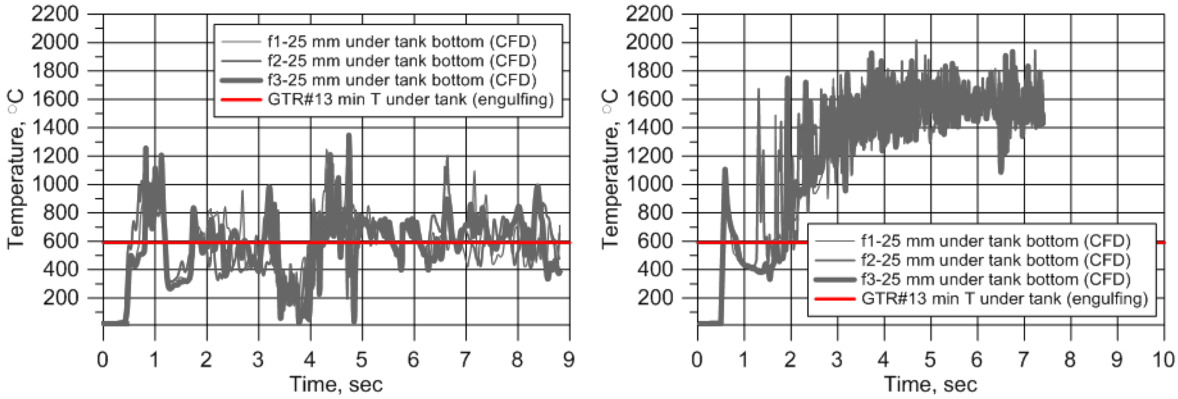

Figure 10. Fire tests with the pipe burner and without wind. Temperatures under the tank: fire tests with HRR/A=0.228 MW/m^2 (left) and HRR/A=1 MW/m^2 (right).

Within first seconds in both numerical tests the under-tank temperatures reached required by GTR#13 and R134 590°C. The reason for observed in simulations temperature difference at location of under-tank thermocouples (25 mm under the tank) is the difference of flame height and air entrainment for two simulated cases with different HRR/A. For the case HRR/A=1 MW/m^2 simulated temperature of about 1500-1600°C is closer to the temperature of propane diffusion flame in air that is reported elsewhere in the range 1530°C [37] - 1980°C [38]. It can be concluded that requirements on maximum temperature at current fire test protocol must be relaxed as they are prohibitive for the use of fire source representing realistic conditions for automobile fires with HRR/A≥1 MW/m^2 and published data for fuel temperature.

3.3 Simulation results: wind 1.8 m/s

The next step was to apply the same wind velocity 1.8 m/s (reported for fire test performed in Buxton, UK) as in the blanket burner numerical experiment. The simulation results are shown in Figure 11.

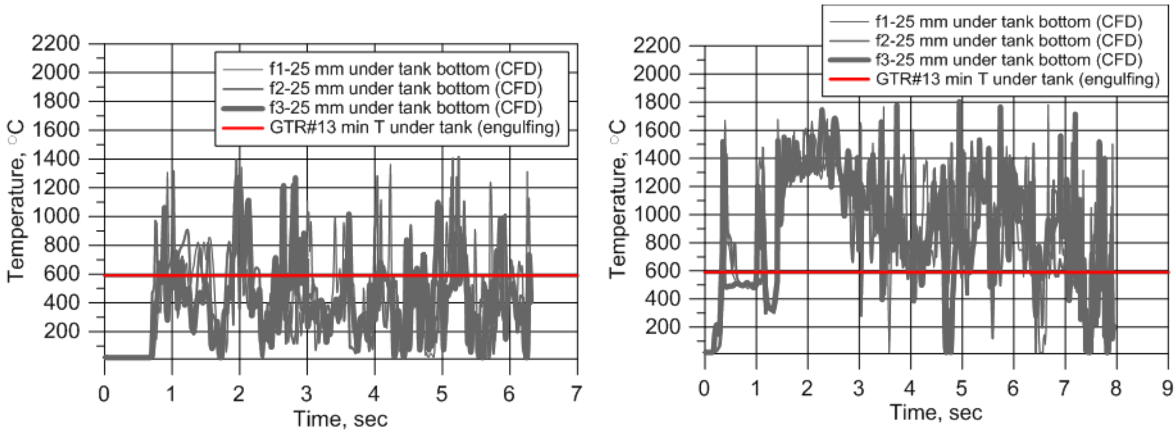

Figure 11. Numerical fire tests with the pipe burner and wind 1.8 m/s. Temperatures under the tank: fire tests with HRR/A=0.228 MW/m^2 (left) and HRR/A=1 MW/m^2 (right).

The pipe burner in the wind conditions reproduces GTR#13 and R134 minimum temperatures when specific HRR/A=1 MW/m^2 (Figure 11, right). However, temperature requirements of GTR#13 and R134 are not always reproduced with HRR/A=0.228 MW/m^2 (Figure 11, left). The pipe burner is wind resistant (at least to wind velocities 1.8 m/s) at HRR/A=1 MW/m^2. This result supports the recommendation of the authors for the GTR#13 fire test protocol to carry out test at HRR/A≥1 MW/m^2. The effect of different shielding and of stronger wind yet to be studied however it is out of scope of this study.

4.0 NUMERICAL STUDY OF IN-SITU LOCALISED FIRE

4.1 Problem formulation

This numerical study imitates fire of a spill of "surrogate" fuel or diesel, both of different burning rates, forming a localised fire area underneath a car. The vehicle geometry was 5.2 m long, 1.82 m wide and 1.47 m high [39]. The onboard hydrogen storage was Type IV tank of 700 bar pressure and 36 L volume [40]. The tank positioning was such that its bottom was at the level of the car bottom (the car bottom is not shown in Figure 12). This fire test involves the vehicle itself, i.e. "Qualification for a specific vehicle installation", as per Method 2 of the GTR#13 and R134 fire test protocol [17], [18]. The localised fire source was under the car covering 250 mm of the tank length from one side, as per GTR#13 and R134 requirements [17], [18] in the section "Localized portion of the fire test". There were 3 TCs located in the localised area of the tank and 3 in the remaining area, following GTR#13 test description (Figure 12).

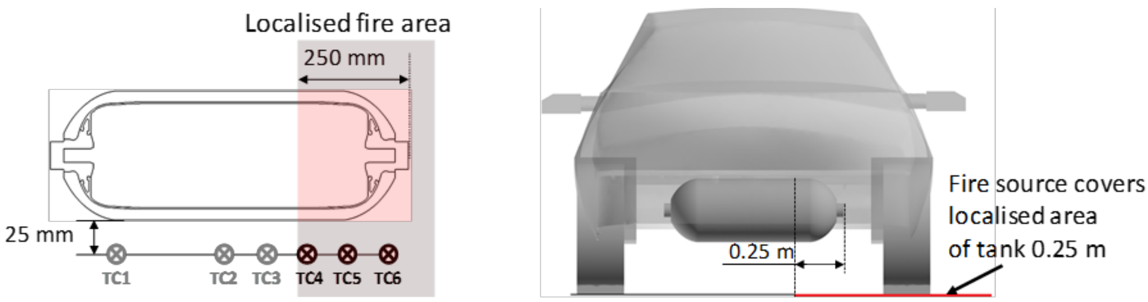

Figure 12. Location of the hydrogen tank and TCs under the tank (left) and location of the cylinder under the car (right).

The calculation domain dimensions were 20x20x15 m. The overall numerical mesh was combined from hexahedral and polyhedral meshes. The total number of control volumes was 816k.

Four in-situ localised fire tests with different HRR/A were investigated numerically. The fuel was propane with flow rates adjusted to those of "surrogate" fuel or diesel to reproduce their burning rates and match the produced HRRs. For instance, for pool fire of about 1 m size the fuel burning rate can be taken as quasi-steady value. Burning rate of diesel for such fire sizes is $\dot{V}$=3.9 mm/min, this is equivalent to $\dot{m}_A$=54.08 g/m^2/s [41]. Hence, for fire source area A=1.9 m^2, $\dot{m}$=103 g/s, the total HRR=4.38 MW and HRR/A=2.3 MW/m^2. The details on all four cases are presented in Table 3.

Table 3. Details of four localised in-situ fires under the car.

Case	Fuels and flow rates	Burner A	HRR	HRR/A
1	C3H8 $\dot{m}$=8.2 g/s	1.9 m^2	0.38 MW	0.2 MW/m^2
2	C3H8 $\dot{m}$=41 g/s	1.9 m^2	1.9 MW	1 MW/m^2
3	C3H8 $\dot{m}$=4.31 g/s	0.2 m^2	0.2 MW	1 MW/m^2
4	C3H8 $\dot{m}$=94.5 g/s	1.9 m^2	4.38 MW	2.3 MW/m^2

Table 3 shows that there are two different spills one with areas 1.9 m^2 (cases 1, 2, 4) and another with area 0.2 m^2 (case 3). Their dimensions were 1.9x1.0 m and 0.5x0.4 m respectively and both covered 250 mm of the tank longitudinal extent as per GTR#13 fire test protocol requirement to the localised fire test (not in-situ!).

4.2 Simulation results

Figure 13 shows the temperature graphs under the tank in four studied in-situ localised fires under the car and comparison with the GTR#13 and R134 minimum temperature requirements for localised fire.

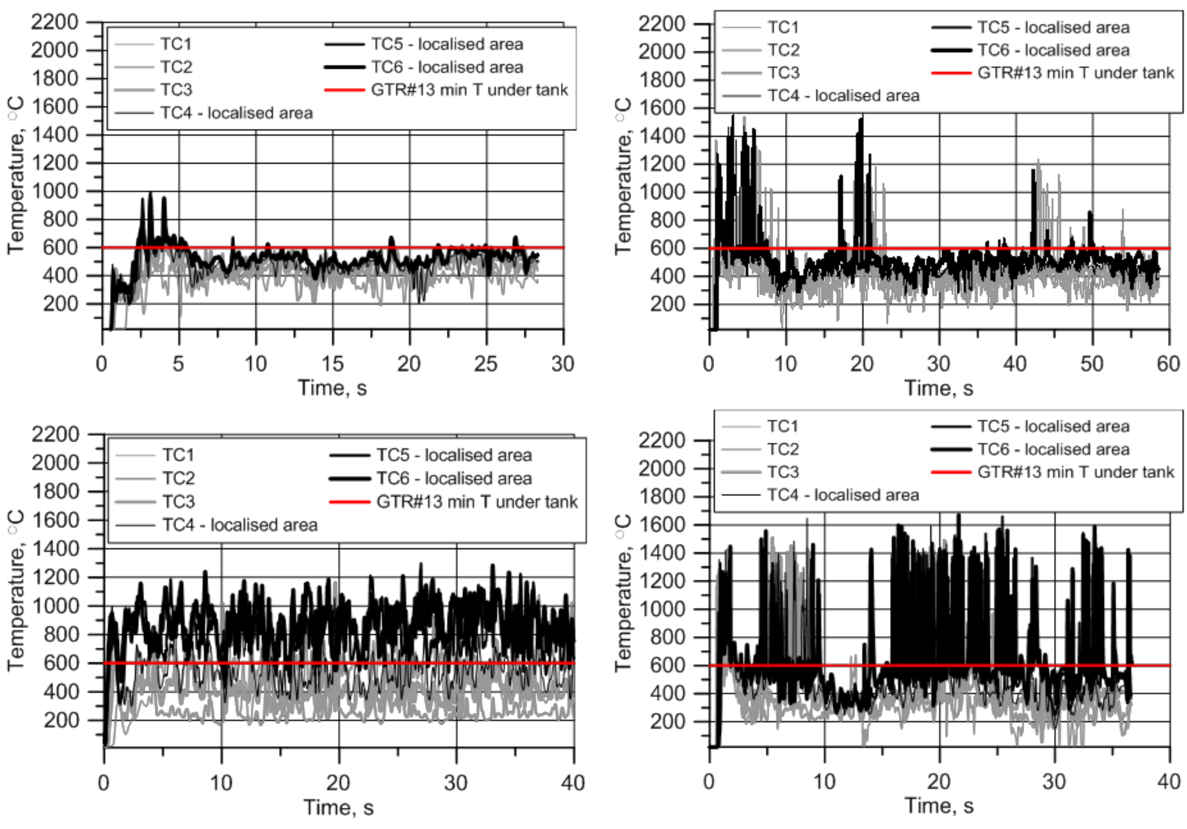

Figure 13. In-situ (under the car) localised fire tests. Temperatures under the tank: Case 1 - HRR/A=0.2 MW/m^2 (left upper); Case 2 - HRR/A=1 MW/m^2 (right upper); Case 3 - HRR/A=1 MW/m^2 (left lower); Case 4 - HRR/A=2.3 MW/m^2 (right lower).

In Cases 1 and 2 (Figure 13, two upper graphs, left and right respectively) the GTR#13 minimum temperature requirements are not satisfied, i.e. the temperatures are below 600°C (the GTR#13 minimum temperature requirement for localised portion of fire test). However, the requirements are satisfied for the Cases 3 and 4 (Figure 13, two lower graphs, left and right respectively). The question is if minimum temperature requirements of GTR#13 could be relaxed for in-situ localised fire test? The authors' opinion is that the requirement can be relaxed. However, the finding that temperature in in-situ localised fire test even with HRR/A=1 MW/m^2 is not satisfied raises an issue of performance of TPRD in real life conditions (as contrary to its performance in idealised test with stand-alone tank).

Figure 14 (left) shows how different are maximum heat fluxes on the tanks in four under-vehicle fires when HRR/A varies in the range from 0.2 MW/m^2 to 2.3 MW/m^2. The expected decrease of heat flux on a tank surface is due to increasing composite surface temperature in a fire. An explanation on difference in heat fluxes for fire tests with HRR/A=2.3 MW/m^2 and 1 MW/m^2 is given below. Figure 14 (right) shows how the change of HRR/A affects the FRR of the tank.

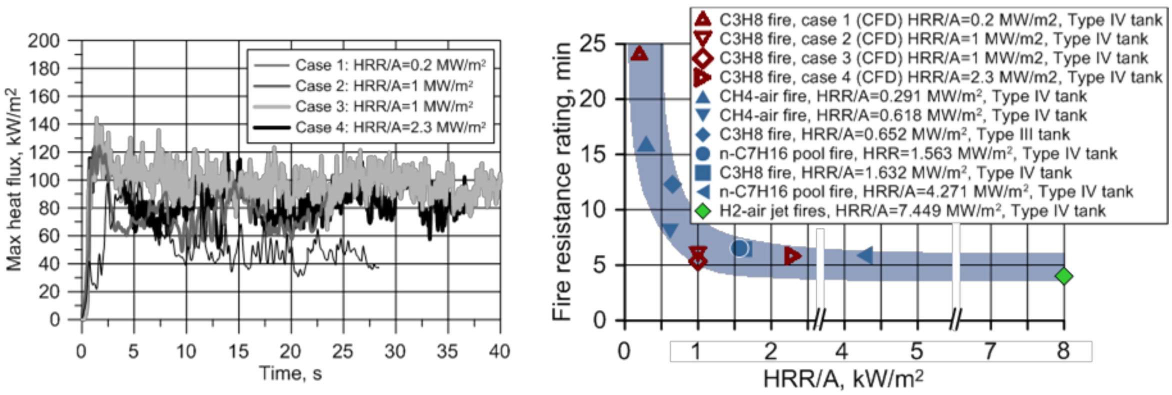

Figure 14. Localised fire under the car: maximum heat fluxes on the tank surface (left), numerically calculated FRR of tanks in Cases 1-4 as a function of HRR/A plotted together with experimental data [3]–[5], [20]–[22] (right).

Table 4. Results of localised in-situ fires (under the car).

Case	Burner A	HRR/A	Heat flux on a tank at the beginning	FRR
1	1.9 m^2	0.2 MW/m^2	$\dot{q}''$=45-50 kW/m^2	24 min
2	1.9 m^2	1 MW/m^2	$\dot{q}''$=80 kW/m^2	6 min
3	0.2 m^2	1 MW/m^2	$\dot{q}''$=90-100 kW/m^2	5 min 20 s
4	1.9 m^2	2.3 MW/m^2	$\dot{q}''$=80-85 kW/m^2	5 min 50 s

Figure 14 (right) and Table 4 show that calculated FRRs for the tank in four in-situ localised fires have the same functional dependence on the HRR/A to that observed experimentally and numerically for the engulfing fire test. The FRR "saturation" onset is observed at HRR/A>1 MW/m^2 similarly to engulfing fire. This confirms the consistency of the suggested correlation of fire resistance rating, FRR, with specific heat release rate, HRR/A, for both engulfing and localised fire tests.

The "unexpected" increase of the FRR for Case 4 (with highest HRR/A=2.3 MW/m^2) to 5 min 50 s compared to Case 3 (smaller HRR/A=1 MW/m^2, and smaller FRR=5 min 20 s) can be explained by the increased of flame height with increased mass flow rate and large combustion products flume outside the car and thus the increase of air entrainment to this flume, including from the space under the car. Dragged into the plume fresh air below the tank from the side opposite to the fire location slightly decreases the maximum heat flux on the tank from 90-100 kW/m^2 to 80-85 kW/m^2.

5.0 CONCLUSIONS

The originality of this work is in the introduction into the fire test protocol an additional to temperature parameter, namely the specific heat release rate, HRR/A, and the definition of its minimum threshold, HRR/A=1 MW/m^2. This is to provide fire test reproducibility in different laboratories and exclude unreasonable approval of tank-TPRD system at fire tests with HRR/A<1 MW/m^2, i.e. below typical for automobile fires values 1-2 MW/m^2.

The rigour of the work is in joint analysis of theoretical, numerical and experimental data on fire tests with high-pressure hydrogen storage. The experimental data and numerical study all have demonstrated that FRR of onboard storage tank is decreasing with HRR/A and "saturates" at HRR/A>1 MW/m^2. For different types of burner and fuel in a burner. Two types of burners were investigated in detail numerically, i.e. the blanket burner and the pipe burner. The minimum temperatures requirements of GTR#13 and R134 for engulfing fire can be reproduced for the blanket burner only in conditions of no wind. The pipe burner is wind resistant (wind 1.8 m/s) and satisfies minimum temperatures requirements of the regulation at HRR/A=1 MW/m^2 and above.

The significance of the study is in the understanding of fire test anatomy to amend the UN GTR#13 fire test protocol. It is concluded that a burner design should provide minimum HRR/A=1 MW/m^2 in an engulfing fire and demonstrate its wind resistance while requirement to burner length 1.65 m can be relaxed. The study suggests relaxing the maximum temperature requirements in GTR#13 test as it can be prohibitive to use the fire source that represents realistic conditions for car fires with HRR/A≥1 MW/m^2. Following requests of first responders the FRR measurement must be included into GTR#13 for engulfing and localised fire tests. This would require carrying out fire test without TPRD (to imitate its failure or blockage during accident). It is demonstrated that in-situ localised fire test differs significantly from idealised fire test with stand-alone tank (consideration should be given to modification of existent localised fire test to better reflect the reality).

6.0 ACKNOWLEDGEMENTS

This research has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 826193 (HyTunnel-CS). This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research. The authors are grateful to Dr Y Tamura of JARI for experimental data used for model validation.

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