OVERVIEW OF FIRST OUTCOMES OF PNR PROJECT HYTUNNEL-CS

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ABSTRACT

The paper presents the first outcomes of the experimental, numerical and theoretical studies performed in the funded by Fuel Cell and Hydrogen Joint Undertaking (FCH2 JU) project HyTunnel-CS (https://hytunnel.net). The project aims to conduct pre-normative research (PNR) to close relevant knowledge gaps and technological bottlenecks in the provision of safety of hydrogen vehicles in underground transportation systems. Pre-normative research performed in the project will ultimately result in three main outputs: harmonised recommendations on response to hydrogen accidents, recommendations for inherently safer use of hydrogen vehicles in underground traffic systems and recommendations for RCS.

The overall concept behind this project is to use inter-disciplinary and inter-sectoral pre-normative research by bringing together theoretical, modelling and experimental studies to maximise the impact. The originality of the overall project concept is the consideration of hydrogen vehicle and underground traffic structure as a *single system* with *integrated safety approach*. The project strives to develop and offer safety strategies reducing or completely excluding hydrogen-specific risks to drivers, passengers, public and first responders in case of hydrogen vehicle accidents within the currently available infrastructure.

1.0 MOTIVATION, AMBITION AND ORGANISATION OF HYTUNNEL-CS PROJECT

A milestone of 3.7 million fuel cell electrical vehicles, 500,000 light commercial vehicles, 45,000 fuel cell trucks and 570 fuel cell trains is foreseen to be reached by 2030 [1]. Those hydrogen-powered vehicles will use underground transport infrastructure, including tunnels, underground parking, bus hubs, garages, maintenance shops, etc. The underground facilities will need to be used by hydrogen vehicles and transport at least at the same level of safety as fossil fuel vehicles.

The main ambition of the funded by Fuel Cell and Hydrogen Joint Undertaking (FCH2 JU) project HyTunnel-CS (https://hytunnel.net) is to allow hydrogen-powered vehicles and hydrogen delivery transport enter underground traffic infrastructure with risks at least at the same level as today's fossil fuel transport or below. The project aims to conduct pre-normative research (PNR) to close relevant knowledge gaps and technological bottlenecks in the provision of safety of hydrogen vehicles in underground transportation systems.

The project formally started 1 March 2019 and will run for 36 months with end date 28 February 2022. The project is a collaboration of 13 European partners coordinated by Ulster University:

- Ulster University (UU), UK;
- Karlsruhe Institute of Technology (KIT), Germany;
- National Center for Scientific Research "Demokritos" (NCSRD), Greece;
- University of South-Eastern Norway (USN), Norway;
- Denmark Technical University (DTU), Denmark;
- Health and Safety Executive (HSE), UK;
- Aragon Hydrogen Foundation (FHa), Spain;
- International Fire Academy (IFA), Switzerland;
- Sapienza University of Rome (URS), Italy;
- Royal Netherlands Standardization Institute (NEN), The Netherlands;
- Federal Public Service Interior (SPFI), Belgium;
- French Alternative Energies and Atomic Energy Commission (CEA), France;
- Pro-Science GmbH (PS), Germany.

The overall concept of this project is based on exploitations of complementarities and synergies of theoretical, numerical and experimental studies in hydrogen and tunnel safety. The project is organised in seven workpackages (WP) each focused at a particular task or phenomena:

- WP1 "The state-of-the-art in safety provisions for underground transportation systems and accident scenarios prioritisation";
- WP2 "Effect of mitigation systems on hydrogen release and dispersion in confined spaces";
- WP3 "Thermal and pressure effects of hydrogen jet fires and structure integrity";
- WP4 "Explosion prevention and mitigation";
- WP5 "First responders' intervention strategies and tactics for hydrogen accidents in underground transportation systems and risk assessment";
- WP6 "Synthesis, outreach and dissemination";
- WP7 "Management".

The project methodology is schematically presented in Fig.1 and the workflow is organised as follows: the state-of-the-art in safety provisions in underground traffic systems, including applicability of existent mitigation concepts to hydrogen, is critically analysed first; relevant national and international Regulations, Codes and Standards (RCS) are identified and examined; accident scenarios are prioritised and relevant scenarios are investigated in joint theoretical, numerical and experimental studies; scientifically intensive research and analysis are carried out in WP2-4; the achieved results are disseminated in the form of beyond the state-of-the-art harmonised recommendations for various group of stakeholders, i.e. "response" oriented WP5 and "designers" oriented WP6. Project coordination and management activities are concentrated in WP7.

The project brings together practical experimental work with theoretical and modelling studies to maximise the impact and applicability of the research and to drive the development of practical outputs. All above makes HyTunnel-CS essentially inter-disciplinary and inter-sectoral project with participating experts in hydrogen and tunnel safety, mass and heat transfer, Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) simulations, experts in experimental techniques with skills to carry out large-scale tests with releases, fires, explosions, etc.

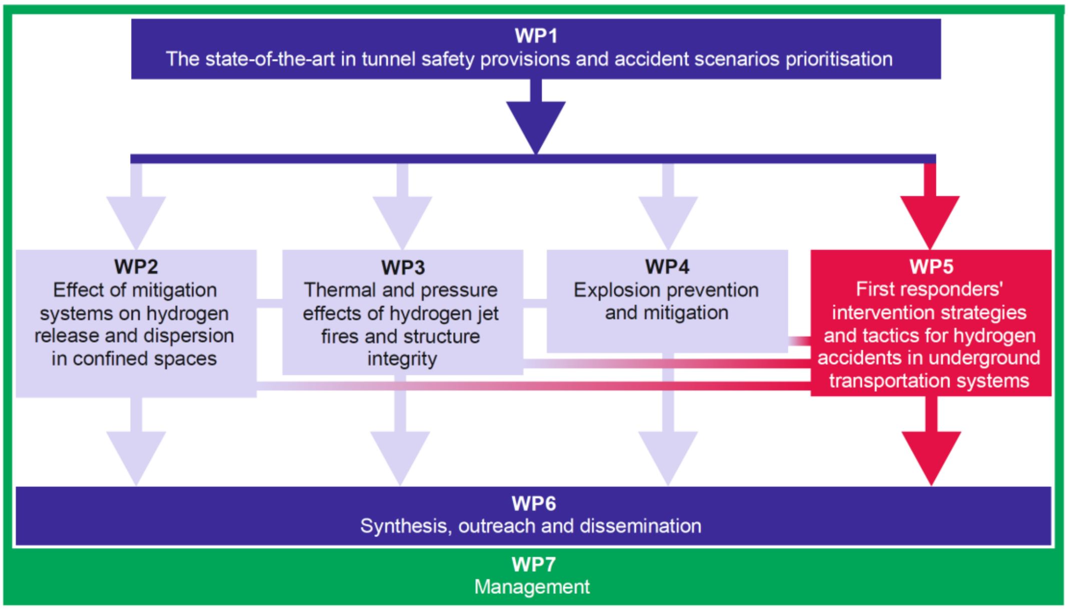


Figure 1. Schematic outline of HyTunnel-CS project organisation and methodology.

The project originality and major strength is in consideration of hydrogen vehicle and underground traffic structure as a *single system* with *integrated safety approach*. Taking into consideration the vehicle adds another dimension to the safety solution space and allows development of flexible and realisable safety strategies. Indeed, update of safety requirements to hydrogen vehicles would be a simpler and cheaper alternative to costly modernisation of tunnel and car parks safety systems to allow hydrogen traffic through underground infrastructure.

The project objectives include the following beyond state-of-the-art developments:

- Critical analysis of effectiveness of conventional safety measures in tunnels and other underground transportation infrastructure;
- Unique experimental data regarding the interaction of hydrogen with safety equipment and systems of underground transportation infrastructure;
- Deeper knowledge of the relevant physics to underpin advanced hydrogen safety engineering and develop innovative prevention and mitigation strategies;
- Development of new contemporary numerical models and engineering tools for relevant physical processes to find hazard distances and perform risk assessment.

The objectives are focused at the three major outcomes, which are the final destination and the focal point of all project activities:

- Harmonised recommendations on response to hydrogen accidents;
- Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems;
- Recommendations for RCS.

All three documents are public deliverables of the project (D5.4, D6.9 and D6.10 respectively) and will be publicly available at the project deliverables page https://hytunnel.net/?page_id=71 after completion of the project. The paper overviews some of the initial project achievements having potential to provide a valuable contribution to the above recommendations and paving the way towards the specified objectives. Due to the limited space only few examples are demonstrated.

2.0 FIRST OUTCOMES OF HYTUNNEL-CS PROJECT

2.1 Efficiency of mechanical ventilation on hydrogen dispersion

Project partner PS conducted series of experiments to investigate hydrogen jet structure and its dispersion in presence of co-, cross- and counter-flow ventilation. Experiments were performed in vessel V220 (A2) having internal diameter 6.0 m, height 8.0 m and internal volume 220 m^3 shown in Fig.2(a). The facility for unignited hydrogen jet dispersion tests was installed between two flanges with inner diameter 1.89 m. Co-, cross- and counter-flow were created using wind machine installed into the flange, Fig.2(b). The parametric studies varied release nozzle diameter (1 – 4 mm), hydrogen mass flow rate (1 and 5 g/s) and ventilation co-, cross- and counter-ventilation velocity (0 – 5 m/s). Hydrogen concentration distribution was measured in axial and radial jet directions. Example of obtained hydrogen concentration contour plots for release nozzle ∅1 mm and mass flow rate 5 g/s are shown in Fig.3 for counter-flow ventilation 5 m/s, co-flow ventilation 5 m/s and no ventilation.

The experimental campaign demonstrated that the ventilation velocity not less than 3.5 m/s, which is the recommended ventilation velocity for traffic tunnels in practice, reduces the length of flammable cloud (4%-75% vol. hydrogen) by 30%-75% for any ventilation orientation - co-flow, counter-flow or cross-flow. Hydrogen-air mixtures with hydrogen vol. fraction 10% vol. have potential of flame acceleration and DDT. Length of 10% vol. hydrogen cloud decreased 10%-38%.

The parametric study detailed results are openly available through HyTunnel-CS community at open data service Zenodo [2] and was subject of benchmark simulations lead by NCSRD [3].

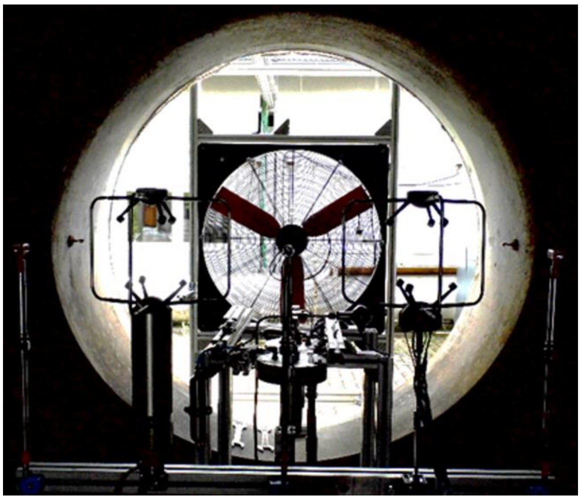
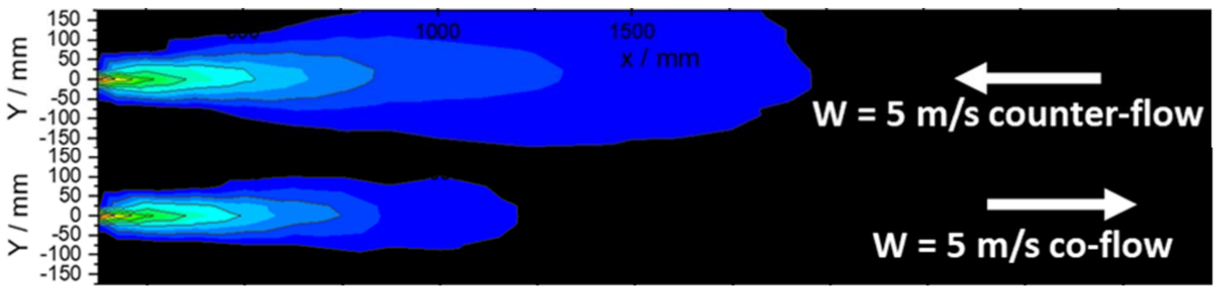
a)  b) 

Figure 2. (a) Experimental vessel V220 (A2), (b) wind machine and flow measurement devices.



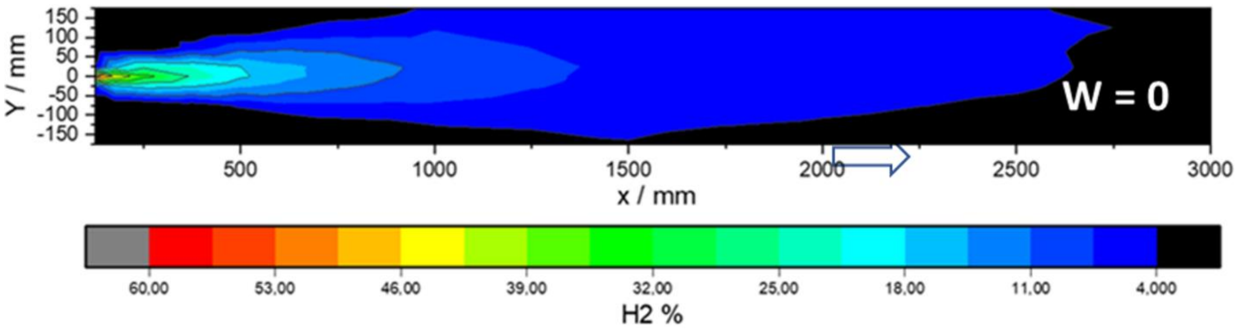


Figure 2. Example of hydrogen vol. fraction distribution for 1 mm nozzle and 5 g/s mass flow rate.

2.2 Safety strategy for design of pressure relief device onboard FCEV

Unignited hydrogen release in underground parking could be considered inherently safer if the thermally activated pressure relief device (TPRD) of fuel cell electrical vehicle (FCEV) is designed to avoid formation of flammable hydrogen-air mixture clouds and under-ceiling layers. Such safety strategy excludes destructive deflagrative combustion and associated pressure and thermal effects even in the presence of ignition sources. Partner UU conducted series of fifteen CFD simulations of unignited blowdown releases accounting realistic vehicle and underground car parking geometry to investigate effect of TPRD release direction and orifice diameter on flammable cloud formation and its maximum extend. Calculation domain replicated real-life underground car park with total floor area A=1115 m^2 and car park height 3 m (in some simulations it was reduced to minimum allowable height 2.1 m). The transient problem formulation considered blowdown of hydrogen storage tank (volume 62.4 l, pressure 700 bar). TPRD orifice diameter varied between ∅0.5 and ∅2.0 mm; release angle varied from 0° to vertical (i.e. vertically down) to 60°. Simulations were performed without effect of mechanical ventilation and with mechanical ventilation rate 10 air changes per hour (ACH). Figure 4 gives example of simulation results for maximum flammable envelop with different TPRD orifice diameter, release angle 45° and ventilation rate 10 ACH.

Analysis of simulation results draw the following conclusions:

- The ventilation does not affect hydrogen flammable clouds formed by releases from TPRD ∅0.5-∅0.75 mm;
- TPRD release direction at the angle 45° deem to be the overall best safety solution. Releases at the angle 0° generate buoyant hydrogen-air plume and form flammable layer under the ceiling. Releases at the angles 0° and 30° provide mixture propagation toward the front and rear wheels, which, if ignited, will contradict to RCS requirements for FCEV.
- Releases from TPRD ∅0.5 and ∅0.75 mm don’t result in a flammable layer formation under car park ceiling for the considered range of ceiling heights (2.1-3.0 m) and ventilation rates - ACH=0 (no ventilation) and ACH=10 (required mechanical ventilation rate in case of fire).
- Releases from TPRDs with a diameter above 0.75 mm have the potential to create a flammable layer, especially in the absence of mechanical ventilation.

All details of this parametric numerical study and its conclusions may be found in [4].

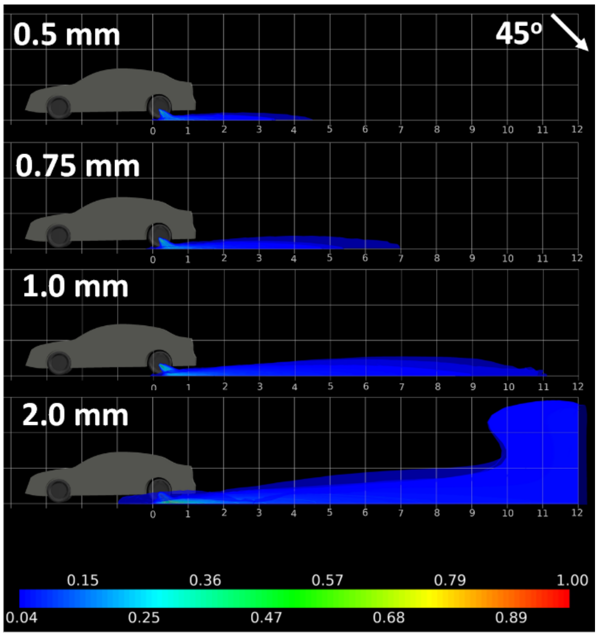


Figure 4. Effect of TPRD diameter on flammable envelope size, release angle 45°, ACH=10.

2.3 Hydrogen jet fire contribution to a car fire heat release rate

Analysis of hydrogen jet fire effect on the heat release rate (HRR) of a burning vehicle was performed by UU. The hydrogen jet fire HRR was calculated based on dynamics of the mass flow rate during blowdown from a realistic hydrogen tank (volume 62.4 l, pressure 700 bar) [5]. A real car fire HRR curve was obtained from [6].

Figure 5 shows the car fire HRR dynamics superimposed with hydrogen jet fire HRR for TPRD diameters ∅2.0, ∅1.0 and ∅0.5 mm. HRR for TPRD ∅2.0 mm reaches peak value 13 MW, though for a very short period of time. On the other hand, HRR for TPRD ∅1.0 mm results in a negligible contribution to a time-dependent vehicle HRR. Combustion of hydrogen equivalent to jet fire from the nozzle ∅0.5 mm provides barely distinguishable contribution to the car fire HRR. It was concluded that for a TPRD diameter ≤ 1 mm, the hydrogen contribution to a vehicle fire HRR may be negligible, though at the cost of a longer duration of the tank blowdown. This is in line with the project strategy to consider tunnel and vehicle as *a single system*. The project also progresses research towards the longer tank fire resistance, possible technical solutions for which are outlined below.

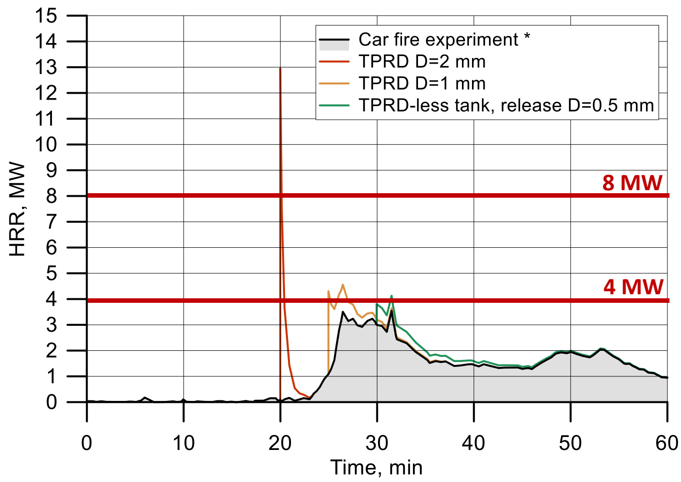


Figure 5. Hydrogen fire contribution to a vehicle fire HRR for TPRD diameters 0.5-2.0 mm.

2.4 Effect of tunnel slope on hydrogen dispersion

As most tunnels are inclined the effect of tunnel slope on hydrogen dispersion was studied numerically by NCSRD. The scenario considered release of 6 kg hydrogen from 700 bar storage below a car via TPRD ∅2.0 and ∅4.0 mm. The horseshoe-shaped tunnel was 200 m long with maximum height 7.1 m and maximum width 9.2 m with two car models 4.2 x 1.8 x 1.3 m placed on the tunnel centre-line. The slopes 0% (0°), 2.5% (1.43°) and 5% (2.86°) were simulated. It was assumed that the tunnel didn't have mechanical ventilation.

Some of the research conclusions are:

- Inclination has small effect on the velocity and concentration field around the car when characteristic length and time scale are small;
- The long-term influence of the inclination is positive: the higher the inclination, the sooner hydrogen will reach near-zero concentrations;
- Adverse inclination effects exist locally, e.g. volume of flammable cloud can be bigger in case of inclination;
- Hydrogen clouds of concentrations above 10% vol., which are more hazardous in case of ignition, are only slightly affected by the slope.

Figure 6 shows the car models and dynamics of hydrogen vol. fraction above the car model for TPRD ∅2.0 mm and tunnel inclination 0%, 2.5% and 5.0%.

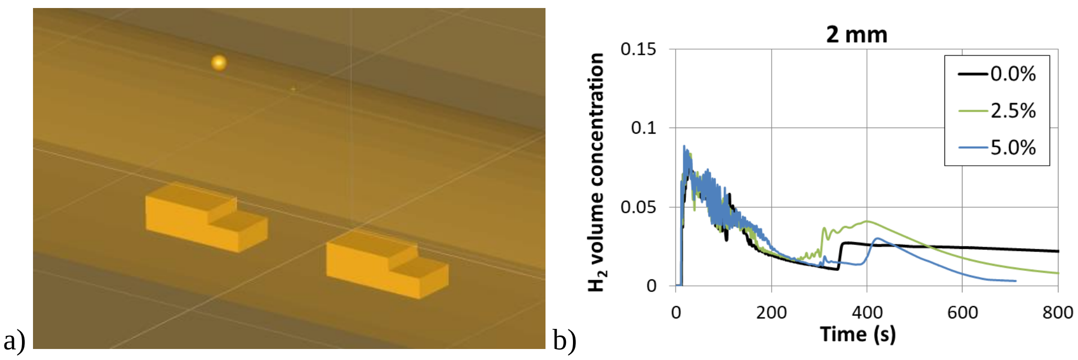


Figure 6. Effect of tunnel slope on flammable mixture formation: (a) car models with hydrogen concentration monitoring location; (b) dynamics of hydrogen volume fraction above the car for tunnel slopes 0%, 2.5% and 5% and TPRD ∅2.0 mm.

2.5 Universal correlation for blast wave decay along the tunnel

Ulster University conducted research on blast wave decay after tank rupture in a tunnel fire which lead to development of the universal correlation [7]. The originality of the research is in complementarities between the validated Computational Fluid Dynamics (CFD) approach, which was used to generate data on blast wave propagation from tanks with broad range of hydrogen inventories (from 0.6 to 6.9 kg), storage pressures (from 350 to 950 bar), along tunnels with different cross-section areas (from 1 to 5 lanes), and similitude analysis, used to create scaled parameters for tunnel length and blast wave. The authors demonstrated that the blast wave in a tunnel decays much slower than in open space; it is dominated by blast wave reflections in a near-field and the blast propagating as planar wave in a far field. Using similitude analysis the authors [7] arrived to the scaled distance along the tunnel $\bar{L}_T = (P_0 L A_T)/(E \cdot AR^n)\,(fL/D_T)^m$ where P_0 is ambient pressure, A_T is tunnel cross section area, L is distance along the tunnel, E is tank energy, AR is aspect ratio, f is friction factor, D_T is tunnel hydraulic diameter, and scaled pressure $\bar{P}_T = \Delta P/(P_0 \bar{L}_T)$, where ΔP is overpressure in the tunnel. The CFD data correlated best with power indices $n = 0.5$ and $m = 1.0$. Figure 7 demonstrates behaviour of the scaled overpressure $\bar{P}_T$ as a function of the scaled location $\bar{L}_T$ based on the CFD simulations. Eventually the conservative form of the universal correlation is $\bar{P}_T = 0.37\bar{L}_T^{-1.35}$, and the best-fit form of the universal correlation is $\bar{P}_T = 0.22\bar{L}_T^{-1.35}$.

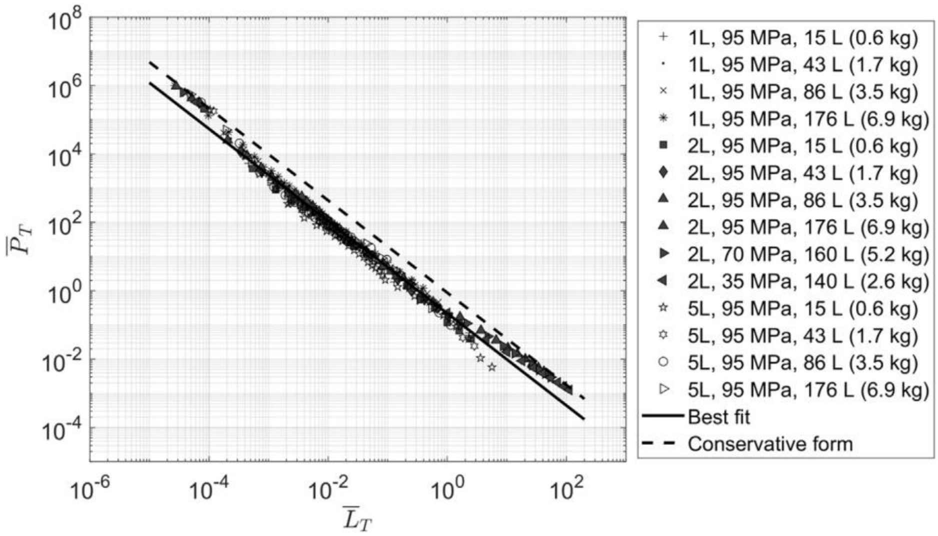


Figure 7. The universal correlation for the blast wave decay after a hydrogen tank rupture in a fire [7].

The correlation encapsulates all factors influencing overpressure in a tunnel and can be used for assessment of consequences of any tank rupture in a tunnel of any cross-section area, aspect ratio and length. At the moment the developed correlation is the only tool available to stakeholders for hazards and associated risk assessment. The validation experiments planned in the HyTunnel-CS project will help to validate the correlation as a practical engineering technique.

2.6 Experimental and modelling research on Pressure Peaking Phenomenon

Combined experimental and numerical research campaign was undertaken by partners USN and UU to further investigate the unique for hydrogen Pressure Peaking Phenomena (PPP), which may result from unignited and ignited hydrogen releases in confined geometries. Though the phenomena was first theoretically predicted back in 2013 [8], so far it was experimentally validated to a limited extend using only small-scale vessel 1 m^3 [9].

In the framework of HyTunnel-CS project the partner USN runs comprehensive experimental programme to generate experimental data on PPP from ignited and unignited hydrogen releases using military grade explosion chamber with total volume 14.9 m^3 and capable to withstand pressures in excess of 10 bar. Figure 8 gives general impression about the explosion chamber design and details of inflow and outflow organisation. The chamber was well instrumented to document dynamics of hydrogen mass rate at inflow, overpressure and temperature in the chamber. Altogether during the first project reporting period there were conducted 11 unignited and 31 ignited experiments with varying hydrogen mass flow rate (up to ca. 12 g/s), outflow vent areas (up to $2 \cdot 10^{-3}$ m^2), resulting PPP overpressure (up to ca. 0.5 bar).

The experiments caried out by USN were used at UU for validation of engineering ignited and unignited PPP models. Altogether 9 unignited and 12 ignited experiments were chosen for validation simulations. The model provided very good agreement with both experimental pressure peak magnitude and experimental pressure peak arrival time. Simulations were performed for constant mass flow rate and experimentally recorded variable mass flow rate. Experimental overpressure dynamics was reproduced exceptionally good in both simulations confirming applicability of the developed engineering tools. Example of overpressure dynamics measured in ignited PPP experiments and corresponding simulation results are given in Figure 9. The PPP experimental data were made available for open access at Zenodo open access service [10]. Engineering ignited and unignited PPP tools are publicly available at the online e-Laboratory of hydrogen engineering tools [11].

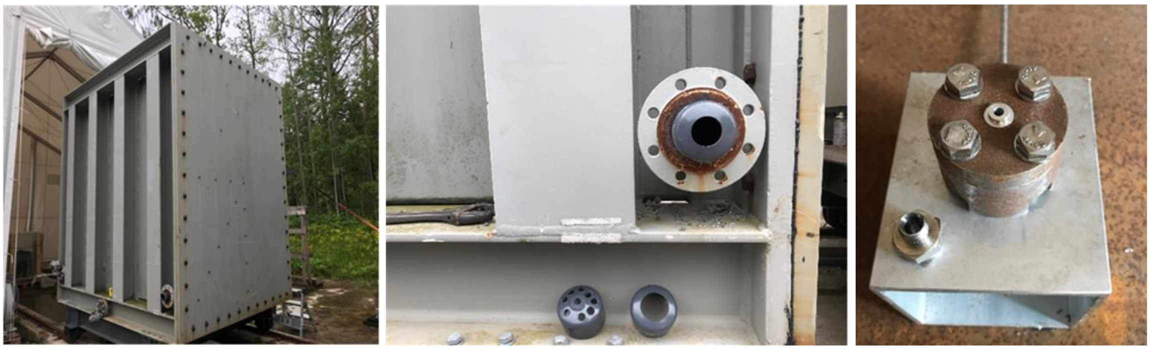


Figure 8. General view of the explosion chamber used by USN in PPP experiments (left); outflow vent pipe (centre); release nozzle ∅4.0 mm (right).

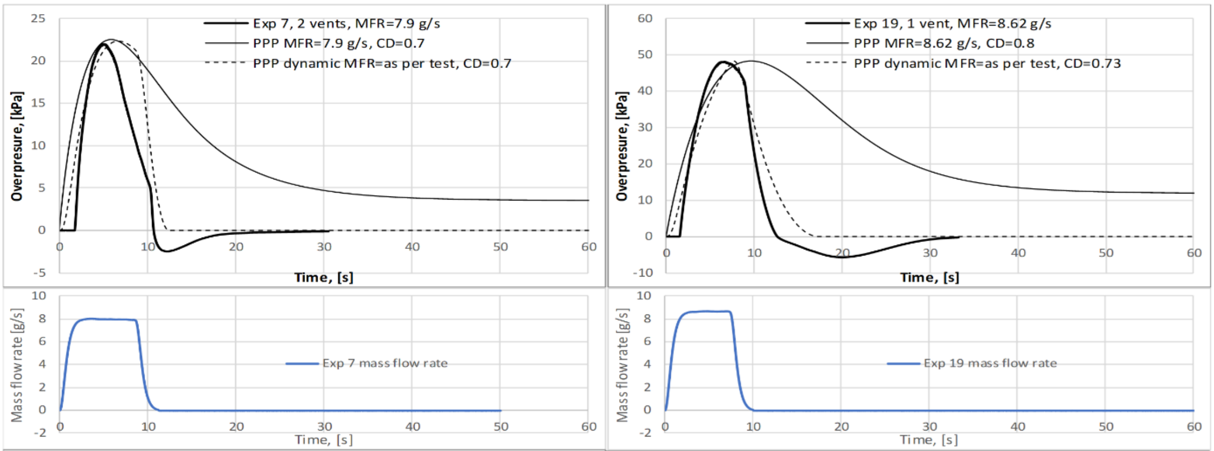


Figure 9. Experimental overpressure dynamics in two ignited PPP experiments in comparison with simulation results for both constant and experimentally measured hydrogen mass flow rate.

2.7 Real tunnel experiments on tank rupture in a fire

CEA recently started the programme of unique hydrogen release, jet fire and tank rupture experiments in a real tunnel, see Fig.10(a). The experimental programme is expected to generate data to provide insight into the relevant physical phenomena, particularly - contribute to the development and improvement of modelling tools, to understand the effect of hydrogen combustion on smoke layer dynamics, dynamics of blast wave and fireball after real composite tank rupture in a fire, etc.

While the experimental programme is still ongoing the initial results are already available for analysis. Thus, it was experimentally confirmed that the fireball generated by tank rupture in a tunnel fire, different from a similar fireball in open space, moves along the tunnel with significant velocity (~20 m/s). Another finding is experimental confirmation of hydrogen combustion contribution to the strength of blast wave, which was predicted in analytical study [12]. Three different tank rupture experiments were performed in CEA tunnel with compressed hydrogen, helium and dummy empty tank. The tanks were filled such that compressed gas energy of hydrogen (50 l, 47 bar) and helium (150 l, 41 bar) were equal. All tanks were ruptured using identical high-explosive charge belt. Figure 11 shows the experimentally measured pressure dynamics from all three rupture tests measured at 38 m and at 205 m from the tank. Despite equal tank energies for compressed hydrogen and helium tanks, the pressure dynamics from hydrogen tank rupture provided consistently higher overpressure, which is attributed to additional energy contributed by hydrogen combustion, thus proving analytical findings [12].

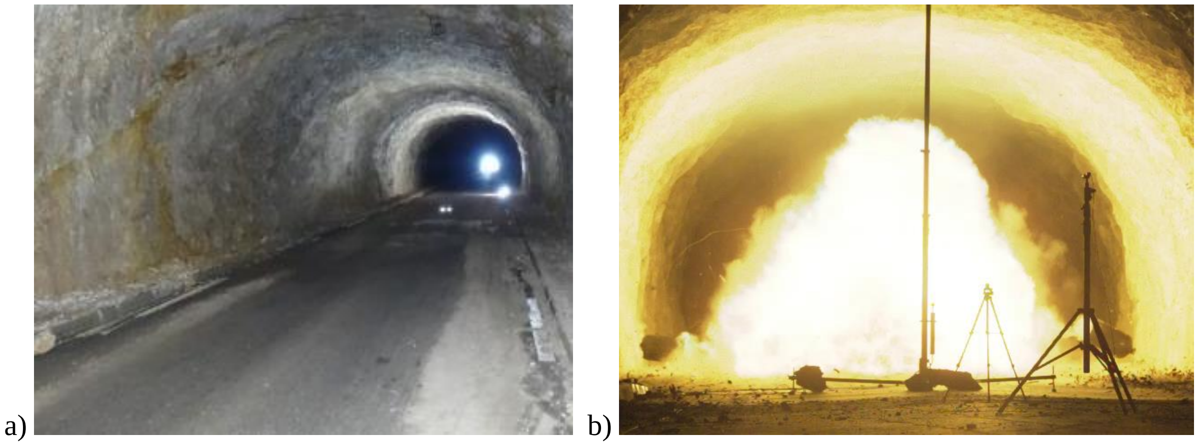


Figure 10. (a) General view of experimental tunnel, (b) hydrogen fireball from tank rupture in a fire.

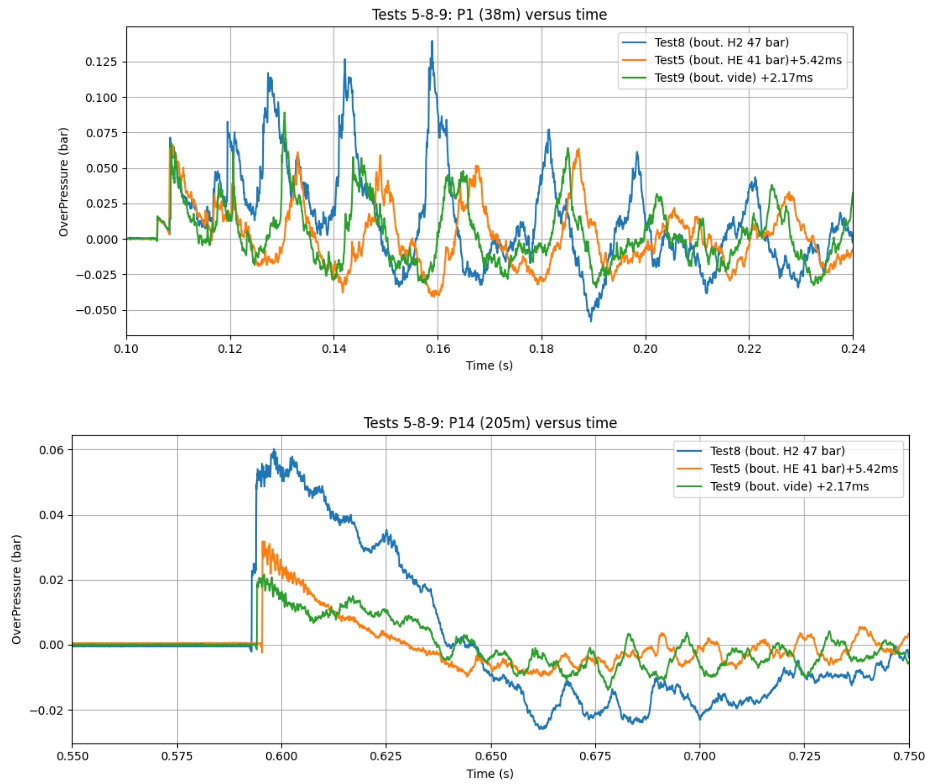


Figure 11. Overpressure dynamics from ruptured compressed hydrogen, helium and dummy empty tanks in tunnel recorded at 38 m (top) and at 205 m (bottom) from the tank.

2.8 Correlation for flame acceleration and DDT in non-uniform hydrogen-air mixtures in presence of obstacles

Correlation for deflagration to detonation transition (DDT) in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles was developed by partner KIT. The development is based on previous research background [13], where linear correlation between the critical expansion ratio σ^* and the ratio of the spacing between the obstacles and the layer thickness, *s/h*, was derived for fast flame propagation based on large scale experiments. Figure 12 illustrates results of experimental studies on flame acceleration in deflagrations from slow to fast flames and the proposed correlation behaviour.

Assessment of DDT potential includes evaluation of

- geometrical factors (confinement degree, scale, etc.);
- flammable mixture (reactivity, uniformity, degree of filling);
- ignition source (electric spark, glow plug, open flame or else);
- history and dynamics of the process (run-up-distance, runway distance to flame acceleration and DDT).

Figure 13 gives different patterns of hydrogen distribution which are considered in the DDT assessment methodology. Eventually the methodology uses the dimensionless ratio L/λ of the characteristic size L over the detonation cell size λ as a measure of detonability of the mixture and criterion for onset of DDT. The developed methodology will be described in detail in the final public deliverable of the project and in a peer-reviewed publications. It is also envisaged that the methodology will be realized as a tool of the aforementioned e-Laboratory of online hydrogen engineering tools [11].

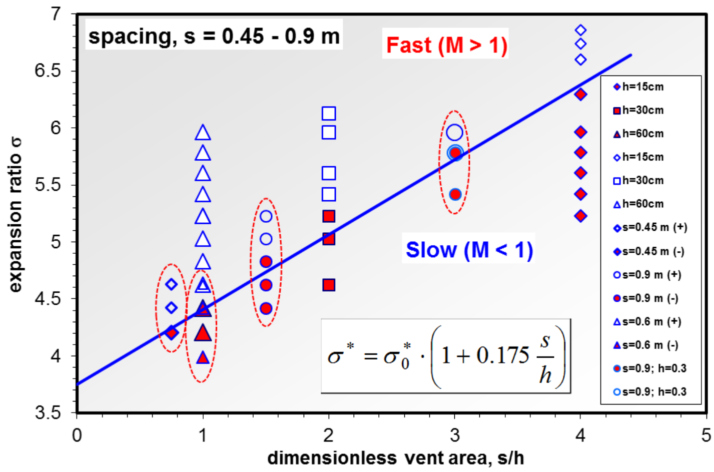


Figure 12. Critical conditions for effective flame acceleration as a function of expansion ratio vs. dimensionless vent area: sonic flame and detonations (open points); subsonic flame (filled points). Different spacing is labelled, [13].

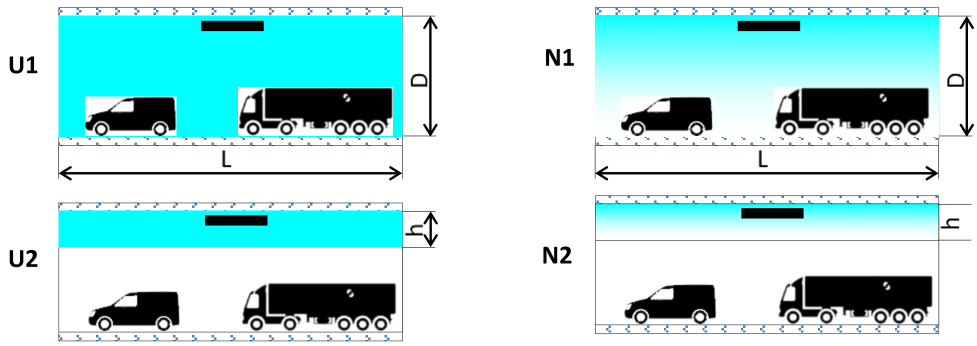


Figure 13. Typical geometry of hydrogen-air cloud inside the tunnel: uniform composition (left); stratified composition (right); fully filled cross-section (top); a semiconfined layer (bottom).

2.9 Safety strategy for design of tank-TPRD system

Performance of a Type IV composite hydrogen storage tank in an engulfing fire was studied by partner UU. The study is based on the use of under-expanded jet theory [14] and developed in HyTunnel-CS project non-adiabatic tank blowdown model [15]. The non-adiabatic blowdown model accounts heat exchange between hydrogen, tank and ambient environment, as well as the composite overwrap resin degradation and liner melting in a fire. Input parameters include TPRD initiation delay time and TPRD diameter. The model was validated and demonstrated to accurately reproduce experimentally measured hydrogen pressure and temperature dynamics, blowdown time, tank's fire-resistance rating (i.e. time to tank rupture in a fire without TPRD).

The performed study allowed to establish the lower limit for TPRD diameter sufficient to prevent the tank rupture in a fire and, at the same time, to reduce the flame length and mitigate the pressure peaking phenomenon in a garage to exclude its destruction. It was demonstrated that the TPRD diameter 0.75 mm for the largest studied tank - 244 l, 700 bar storage pressure – was sufficient to prevent tank rupture when combined with TPRD activation time 180 s and additional hydrogen release due to the liner melting. Figure 14 illustrates performance of 244 l storage tank with TPRD orifices ∅0.5 mm (leading to tank rupture), ∅0.75 mm and ∅1.0 mm (leading to liner melting and safe tank blowdown). Detailed description of the model and safety strategy for design of tank-TPRD system are given in recent publication [15].

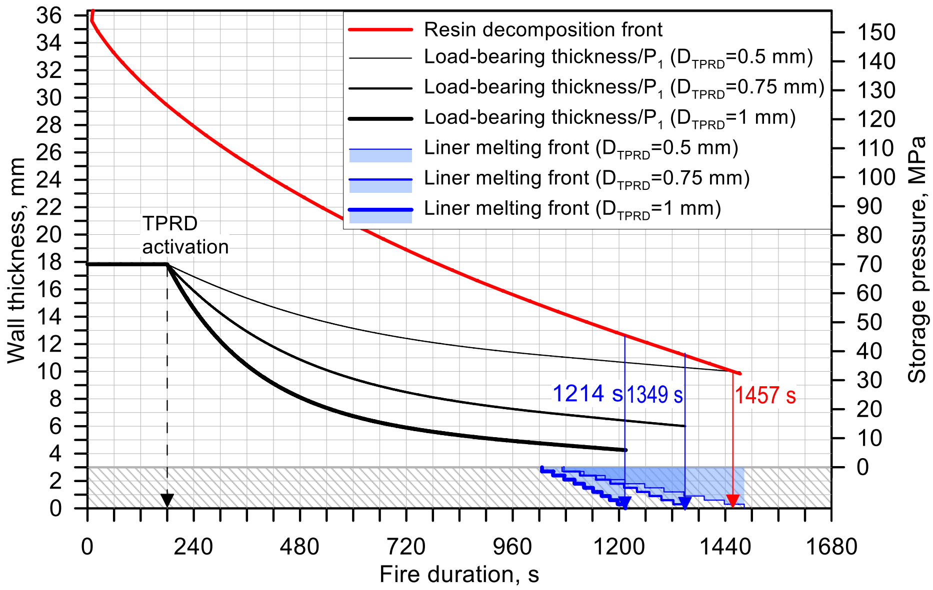


Figure 14. Example of tank-TPRD performance in fire: simulation of load-bearing tank wall thickness dynamics for hydrogen release from TPRD with activation time 180 s and orifice ∅0.5 mm, ∅0.75 mm and ∅1.0 mm.

2.10 Explosion-free in a fire tank technology

In the framework of the project the partner UU continues to develop its IP "Composite pressure vessel for hydrogen storage" implementing explosion-free in a fire hydrogen tank technology. Detailed description of the technology is available in [16]; the technology essence is in combination of composite tank wall materials allowing liner melting and safe tank blowdown before reaching loss of tank wall load bearing ability in a fire. Different tank prototype designs were developed to validate the technology for high-pressure (700 bar) storage tanks in the past and tested in compliance with GTR #13 fire test protocol requirements [17]. During the tests the protypes demonstrated expected performance in a fire: not being equipped by TPRD all tanks retained structural integrity and released hydrogen due to liner melting without rupture. Figure 15 shows the tank prototype during different stages of the fire test. Figure 16 gives hydrogen pressure dynamics in the tank during the test. Initial pressure growth due to tank heating stops at 6 min from the start of the test due to hydrogen leakage, after which the pressure decreases and the tank is completely emptied at 20 min. This blowdown process is not associated with any increase of thermal or pressure hazards as hydrogen release is achieved through microleaks. More engineering prototypes are planned to be tested during HyTunnel-CS project at the sites of partner organisations conducting experimental research.

The technology fits the *single system* concept of the project and enables *integrated safety* approach. Indeed, the technology implementation excludes devastating blast wave, fireballs, projectiles, long flames, pressure peaking and, eventually, loss of life as a result of FCEV fire accident. Ultimately, it allows to fulfil the main ambitions of the project facilitating hydrogen vehicles entering underground traffic systems at risk below or the same as for fossil fuel transport.

Figure 15. Fire test of explosion-free tank demonstrating tank integrity during the localised fire test stage (left), engulfing fire stage (centre), end of fire test (right).

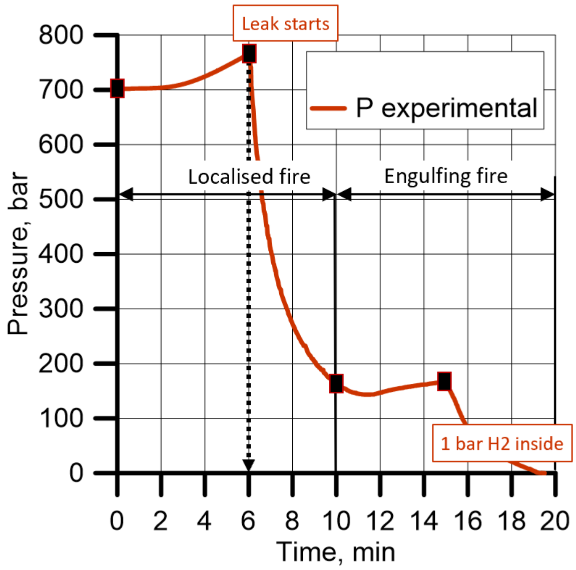


Figure 16. Pressure dynamics in the explosion-free tank during the fire test.

3.0 CONCLUSIONS

The project HyTunnel-CS performs pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces. The main ambition of the project – to enable hydrogen vehicles entering underground traffic systems at risk below or the same as for fossil fuel vehicles – is being achieved via unique approach considering tunnel and vehicle as *a single system*.

The paper provided brief overview of some initial results of the project fulfilling its specific objectives:

- Efficiency of mechanical ventilation on hydrogen dispersion;
- Safety strategy for design of pressure relief device onboard FCEV;
- Hydrogen jet fire contribution to a car fire heat release rate;
- Effect of tunnel slope on hydrogen dispersion;
- Universal correlation for blast wave decay along the tunnel;
- Experimental and modelling research on Pressure Peaking Phenomenon;
- Real tunnel experiments on tank rupture in a fire;
- Correlation for flame acceleration and DDT in non-uniform hydrogen-air mixtures in presence of obstacles;
- Safety strategy for design of tank-TPRD system;
- Explosion-free in a fire tank technology.

The complete description of project results will be detailed in the corresponding final reports on analytical, numerical and experimental studies, which will be public deliverables and available at the project website https://hytunnel.net/.

The research results will feed into and underpin three major project outcomes:

- Harmonised recommendations on response to hydrogen accidents;
- Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems;
- Recommendations for RCS.

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