Group: Hydrogen

Fundamental Behaviour of Hydrogen to Applied Accident Consequence Analysis for Hydrogen as a Safe Energy Carrier

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Introduction

In 2019 the Hydrogen Group continued to develop the in-house specialized CFD codes, GASFLOW and COM3D, and conducted several experimental programs to deepen the understanding of the mixing behavior and the transient combustion phenomena, flame acceleration and deflagration-detonation-transition, of accidentally released hydrogen. Members of the group are actively transferring their insights and expertise into the respective IEA Hydrogen Task 37, the standards committees of ISO (TC 197), CEN/CENELEC (TC 6) and in the European Hydrogen Safety Panel. Among other third party funded projects the Hydrogen Group has been conducting ambitious experimental programs for the European Fuel Cell and Hydrogen Joint Undertaking (FCH JU) funded projects PRESLHY - Pre-normative research for the safe use of liquid hydrogen - and HyTunnel-CS - Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces. The report for 2019 will focus on some highlights provided by the Hydrogen Group in the field of hydrogen safety in tunnels and confined spaces.

Hydrogen Fire Suppression in Traffic Tunnels

The Hydrogen Group supported by the Pro-Science team has performed more than 600 tests to investigate the effect of mechanical ventilation on hydrogen jet structure and dispersion. The experiment was integrated in the huge test vessel V220, see Figure 1a,b. A powerful fan was installed in one of the two main ports of the vessel. Between the ports a 6 m long test domain was arranged to mimic a scaled down cut-out of a tunnel with an accidental release of hydrogen. Thirty different configurations were examined by changing the H_2 mass flow rate from 1 to 5 g/s and the air flow velocity in the range 1.5- 5 m/s with co-aligned, opposite and tranversal direction of the ventilation flow in relation to the hydrogen jet direction.

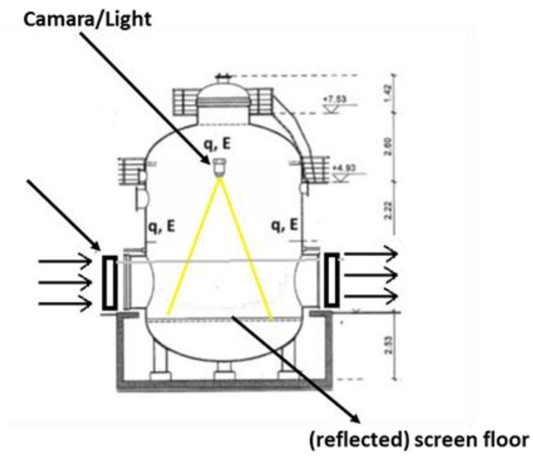


Figure 1: a Experimental set-up of tunnel ventilation experiments in HYKA V220 test vessel;

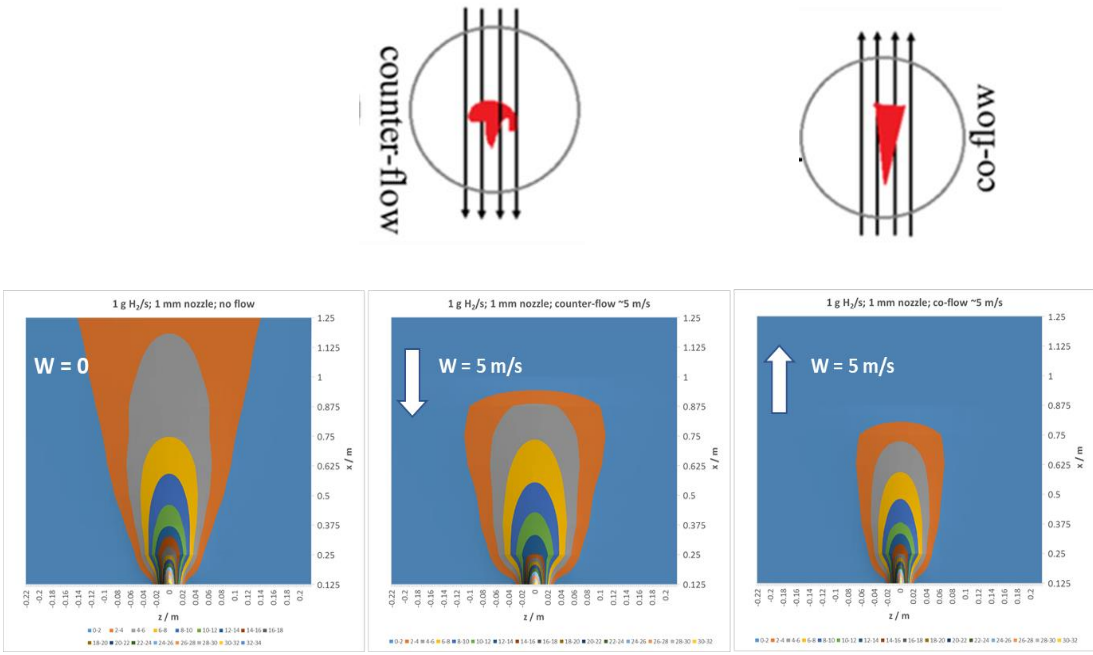
Figure 1: b View from downstream on the ventilated tunnel segment with central fan

The aim of the experimental campaign was to determine the hazard distances as function of hydrogen mass flow rate, ventilation air flow velocity and relative release direction. It was found that for all examined configurations, the mechanical ventilation led to a considerable size reduction of the pre-mixed cloud defined by the flammable mixture.

Relevant tests have been selected for uploading of the corresponding result files on the HyTunnel-CS open data repository. These data will be further used for code validations.

Hydrogen Fire Suppression in Traffic Tunnels

Fires are representing typical hazards in tunnels and some devastating fire accidents where initiating the development of the European tunnel safety directive [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004L0054&from=en]. As hydrogen fires show some quite distinct characteristics and different behavior compared to conventional fires and the current version of the European tunnel safety directive does not address hydrogen as an alternative fuel, the applicability of conventional mitigation technology has to be evaluated. The suppression effects of installed fire safety systems and the special accidental conditions have been



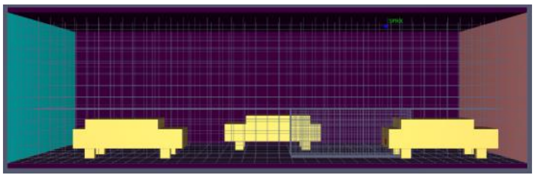
(a) (b) (c)

Figure 2: Measured concentrations in horizontal plane at height of release nozzle; (a) without ventilation, (b) with counterflow ventilation (c) with co-flow ventilation

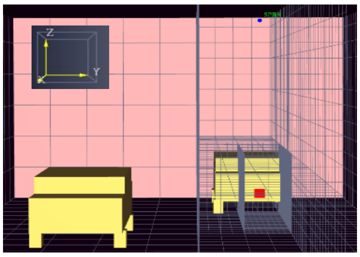
studied experimentally and theoretically by numerical simulations.

The CFD code Fire Dynamics Simulator (FDS) [https://www.nist.gov/services-resources/software/fds-and-smokeview], developed by the US NIST and widely used in the fire safety community, has been adopted to analyze the hydrogen fire generated from an accidental release of hydrogen. The simulations account for the effects of water sprays and/or in oxygen starving conditions. The main variations concern the leaking mass flow rates of the hydrogen source, the mass flow rates of water injection, and /or different droplet sizes.

Figure 3 shows the simplified 3D tunnel section which is modeled geometrically together with three cars. One of the cars releases its high pressure hydrogen inventory via a nozzle on the lower rear side, as a primary fire is assumed to open the temperature activated pressure release device (TPRD). The release nozzle pointing backwards from the concerned car, is marked with red color in Figure 3.



(a) Longitudial view



(b) Transverse view

Figure 3: Numerical mesh of the simulated road tunnel segment with 3 cars,
one of them (on the right hand side) releasing hydrogen through a nozzle (red dot)

The gas temperature and gas compositions have been computed with and without water spray and with a variation of oxygen depletion in the concerned tunnel segment, i.e., less than 21 vol. % in normal air. The simulation cases are put together into the following table. The transient thermal state of the gas in the control volumes, e.g., temperature and steam fraction, have been calculated. The results are used to derive recommendations whether the environment in the tunnel is suitable for fire control, evacuation and rescue operations under the heat release rates of the hydrogen fire and for the selected water spray and oxygen depletion conditions.

The following preliminary results are obtained by the FDS simulations. The temperatures of as shown in Figure 4 indicate a cooling effect of the water spray on the fire, although the temperature decrease is not that much due to the relatively low mass flow rate of water in that simulation case. It is interesting that for some cases the gas temperature with spray is higher than without spray (compare black and blue line in Figure 4). The reason for this surprising behavior is, that the hydrogen combustion is intensified by the turbulence and mixing effect induced by the spray droplet momentum.

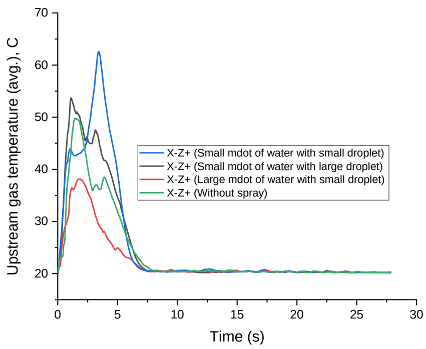


Figure 4: Gas temperature changes in upstream caused by water spray

The humidity (steam fraction) is also computed as it is a classical indicator for the impact on human beings. Obviously, the humidity at tunnel exit is increased due to the operation of water spray. It means that some droplets must evaporate and remove tangible heat of hydrogen fire. However, although this might have an

Table 1.1: Calculation cases of hydrogen fires suppressed by water sprays or oxygen depletions

	Water spray				Oxygen depletion		
	Small mass flow rate of water		Large mass flow rate of water		Slight starving of O_2	Medium starving of O_2	Serious starving of O_2
	Small droplet	Large droplet	Small droplet	Large droplet			
Small mass flow rate of H_2	1	3	5	7	a	c	e
Large mass flow rate of H_2	2	4	6	8	b	d	f

impact on first responders strategies, there is practically no effect of the increased humidity on the reaction kinetics. Another observation is, that a higher water spray mass flux does not further improve the situation.

So, it may be concluded that up to a certain limit a larger mass flow rate of spray brings better cooling effect and produces a higher steam fraction in the gas mixture. In certain conditions the spray may increase turbulence levels and promote faster combustion. The simulations with high degree of oxygen depletion show that even under extreme conditions hydrogen is always burnt almost completely and no flammable mixture is leaving the simulation domain. So a transfer of unburnt hydrogen into another segment or into the ventilation ducts is very unlikely.

Consequence analysis of hydrogen explosions in tunnels

In the more unlikely case of late ignition of released and pre-mixed hydrogen in the tunnel, fire phenomena become less relevant and mitigation of the potential explosion effects becomes more important. Without proper mitigation, the blast waves generated in a local hydrogen combustion event might travel a much longer distance in the tube like tunnel structures than in a free environment. To provide a reference scenario a typical tunnel accident with late ignition was analysed with the in-house code GASFLOW-MPI [1]. This reference scenario consisted of a tunnel segment with two parallel lanes in the same direction (two separate tubes), with a very mild inclination, but without ventilation or spray activation, i.e. without accounting for any active mitigation technology.

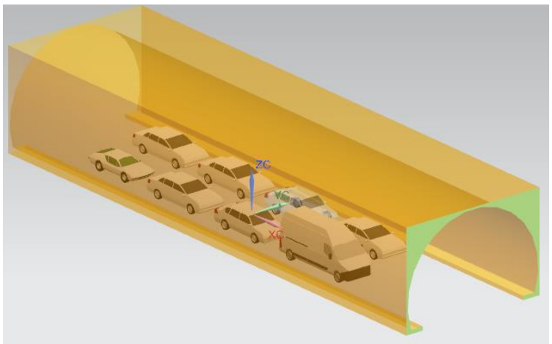
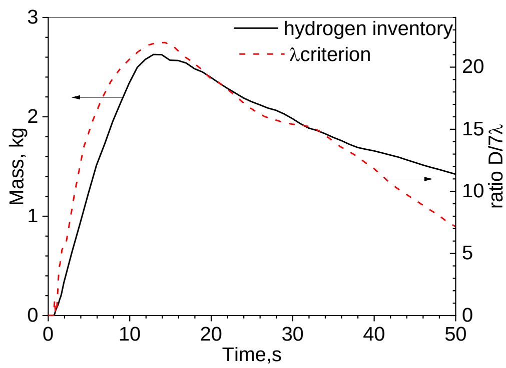


Figure 5: Tunnel segment modeled for late ignition / explosion scenario

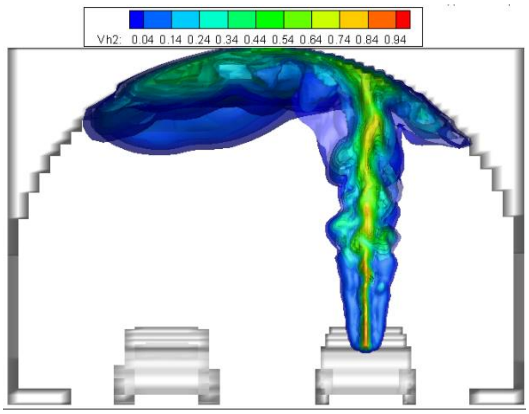
It was assumed that the inventory of 5 kg stored at one hydrogen driven car under high pressure is released via the TPRD at the rear of the car, similar as for the fire simulations above. For the release phase GASFLOW-MPI determines the time dependent mass of hydrogen included in the flammable cloud and the potential for a deflagration-to-detonation transition (DDT) in this premixed system (see Figure 6 top). This information was used to determine the most conservative location and timing for an ignition. So ignition was assumed for maximum flammable mass at about 12.5 s after start of the release in a central position of the premixed cloud with a hydrogen concentration close to stoichiometry (about 30%). The ignition location close to the central ceiling maybe easily motivated, as in tunnels with such a horse-shoe shaped cross-section the electric supply lines for light and ventilation are installed typically there. However, an accidental ignition by a spark is considered a weak ignition source, as it won't initiate a detonation directly.

After the weak ignition GASFLOW-MPI determines the transient pressure loads generated in the deflagration. Although a DDT may not be ruled out, because of the high degree of confinement and obstruction, it is difficult to determine the exact location and further developments of a detonation. However, the loads generated by the deflagration, with local maxima in the order of 3 bar (see Figure 7), are strong enough to damage all involved vehicles seriously and eventually to destroy the tunnel structure.



a) Hydrogen integral mass and λ criterion in the area

Figure 6: a): time evolution of flammable mass and relative diameter of DDT capable cloud;



b) Y-z-cut of hydrogen concentration and the location of ignition

Figure 6: b) vertical cut of flammable cloud at critical ignition time (12.5 s) and critical ignition location (red dot)

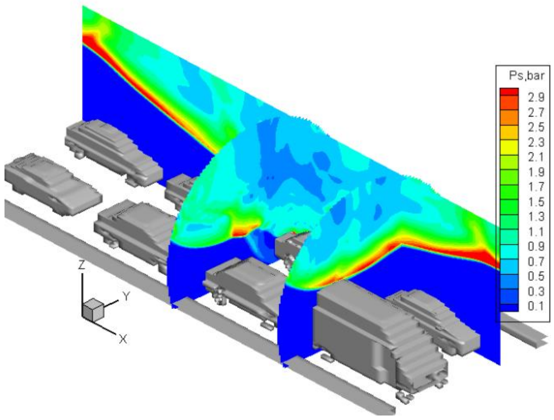


Figure 7: Blast wave caused by hydrogen deflagration reaches the car roofs

It has to be stressed, that this scenario is assumed to have very low probability. It is mainly used as a reference for evaluating the effectiveness of mitigation measures against explosion scenarios. The next chapter describes such an evaluation for water sprays, which are typically installed in larger tunnels.

Study of attenuation effect of water droplets on blast waves

To gain a better understanding, first the different attenuation mechanisms, like momentum absorption, thermal absorption, reflection and droplet breakup, were systematically assessed with simplified analytical models. Influencing parameters, such as droplet size and liquid phase concentration were analysed. A literature survey provided an overview of similar research and allowed to identify high quality validation data generated in well instrumented experiments.

A suitable droplet model, addressing the main phenomena droplet drag forces and droplet breakup, has been developed and implemented in the COM3D code. The correlations and parameters needed for the drag coefficient and for the breakup time and secondary droplet size have been tuned to reproduce the results published in [A. Chauvin et al. “Investigation of the attenuation of a shock wave passing through a water spray”. In: *International Symposium on Military Aspects of Blast and Shock (MABS) 21* (2010]. Figure 8 depicts the channel used in these experiments with the high pressure driver region, a low pressure blast wave travel zone and the droplet cloud zone.

The results achieved with the COM3D implemented model are compared to the experimental results in Figure 9. The simulations reproduce the results qualitatively and quantitatively reasonably well. In particular the early critical phase of droplet atomization is captured very well.

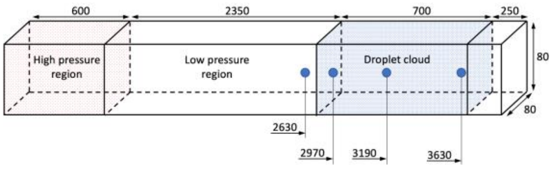


Figure 8: Experimental set-up for the Chauvin experiments

Subsequently, using the developed model, simulations have been conducted to plan middle sized water spray / shock wave interaction experiments in the hydrogen test facility V220 of the hydrogen test center HYKA. Hydrogen is detonated in a combustion unit, what induces a shockwave. The pressure propagation in the absence and presence of a droplet cloud has been computed. The results will be used to tune the experimental layout.

Finally, it is planned to use the COM3D code with these new extensions to assess the mitigating effects of conventional water sprays and modern mist system for hydrogen explosion scenarios in traffic tunnels, as described above.

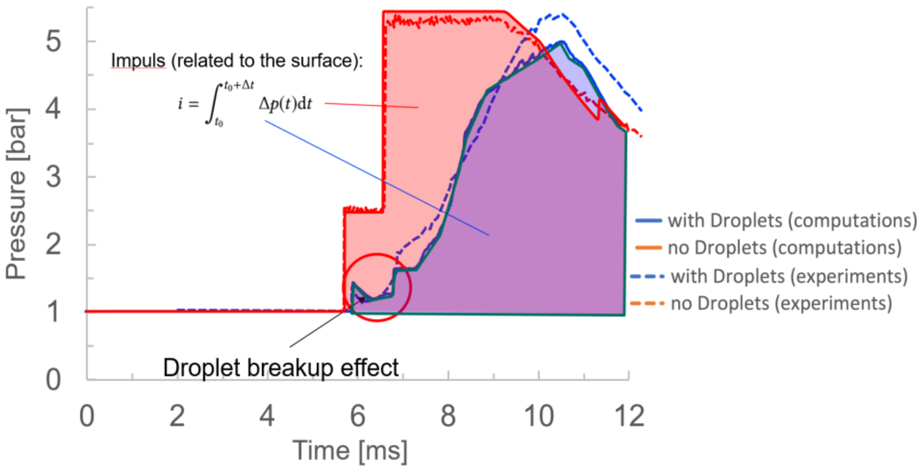


Figure 9: Comparison of COM3D results and measured pressure at point 3190 without (red lines) and with droplet cloud (blue lines)

References

[1] Li, Y.; Xiao, J.; Zhang, H.; Breitung, W.; Travis, J.; Kuznetsov, M.; Jordan, T.: ANALYSIS OF TRANSIENT HYDROGEN RELEASE, DISPERSION AND EXPLOSION IN A TUNNEL WITH FUEL CELL VEHICLES USING ALL-SPEED CFD CODE GASFLOW-MPI, 8th International Conference on Hydrogen Safety, Adelaide, Australia, 24-26 September 2019.