Numerical Simulation And Safety Evaluation Of Tunnel Accidents With A Hydrogen Powered Vehicle

W. Breitung*, U. Bielert*, G. Necker*, A. Veser*
F.-J. Wetzel†, K. Pehr†

* Flow and Combustion Engineering Division, Institute of Nuclear and Energy Technologies, Research Center Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany, breitung@iket.fzk.de, Tel.: 49-7247-82-2463, Fax: 49-7247-82-5987
† BMW AG, 80788 Munich, Germany

Abstract

Computational fluid dynamics (CFD) calculations were performed simulating tunnel accidents with a hydrogen powered vehicle. The investigated scenarios assume damage of the LH\textsubscript{2} system, release of gaseous H\textsubscript{2}, mixing with air, ignition and finally combustion. Gaseous H\textsubscript{2} rises to the tunnel ceiling forming a strongly stratified mixture. Shape, size, inner structure and temperature of the evolving H\textsubscript{2}-air clouds were calculated. Using new developed criteria, the time and space regions with potential for fast combustion modes were identified. For the given H\textsubscript{2}-sources the combustion regime is governed by the ignition time. For late ignition a slow and incomplete combustion of the partly premixed H\textsubscript{2}-air cloud along the tunnel ceiling is predicted. For early ignition a standing diffusion flame develops with dimensions and heat fluxes determined by the H\textsubscript{2} release rate. Temperature, oxygen and flow velocity fields during the combustion were computed. In both cases only minor pressures are generated. The highest damage potential appears to exist for intermediate ignition times. Design measures can be used to limit the risk of hydrogen driven vehicles to the level of gasoline cars.

Keywords: safety, simulation, car, hydrogen distribution, combustion

1. Introduction

The acceptance of future hydrogen powered passenger cars requires not only an attractive price, good automotive performance, and design for normal operation, but also a safety standard for accident situations which is comparable to today’s gasoline technology. Especially during the transition phase from carbon to hydrogen based economy where both systems will be in direct competition, risk limitation to currently accepted levels will be important for consumers and manufacturers as well (product liability).

The safety relevant differences between hydrogen and other vehicle fuels, as e.g. gasoline vapor or natural gas, are due to the unique physical, chemical and thermodynamic properties of hydrogen gas. Transport processes in H\textsubscript{2}-air mixtures are enhanced due to the large molecular diffusion coefficient and low molecular weight (buoyancy effects). H\textsubscript{2}-air has the lowest ignition energy of all combustible gases. Once ignited, H\textsubscript{2}-air mixtures burn much faster than other equivalent fuel-air mixtures. H\textsubscript{2}-air flame surfaces are exceptionally unstable, which can lead to rapidly growing flame areas, flame speeds and high pressure loads under appropriate conditions. These specific hydrogen properties can result in largely different accident progressions and consequences, compared to conventional fuels. It is therefore important to understand the safety implications resulting from the use of hydrogen as a vehicle fuel.
2. Objectives

A reasonable strategy towards an acceptable risk level in new technologies is to investigate a hierarchy of postulated accident classes, starting with the worst-cases, and proceeding towards less severe events. Accident sequences which are physically possible, but lead to unacceptable risks must be excluded by design measures.

In case of LH$_2$-powered cars the worst-case events are connected with sudden catastrophic failure of the cryogenic tank, because this would result in the maximum possible release rate for hydrogen and combustion energy. Full scale experiments have shown that this type of accidents is practically eliminated for modern LH$_2$ tanks, due to their excellent mechanical stability [1].

The next less severe class of accidents concerns events with intact tank body but unrestricted blow-down of a gaseous hydrogen jet from the tank or a connected system into the environment. The combustion rate after a given hydrogen release can depend sensitively on the scale and geometry of the enclosure because they influence mixture formation and turbulence generation. The highest flame speeds and the largest damage potentials develop in obstructed and confined geometries. These general facts about turbulent combustion phenomena suggest that H$_2$ jet releases in a tunnel geometry are likely to create bounding conditions for possible accident consequences. Therefore tunnel accidents were selected for the present study. The analysis procedure and the applied numerical tools were developed and verified for other industrial safety investigations [2].

The objectives are calculation of the H$_2$ distribution and mixing phenomena, evaluation of the potential for fast combustion modes, simulation of the combustion process with different ignition conditions, and estimation of the resulting pressure loads, temperature loads, flow velocities and oxygen distributions.

3. Scenarios and modelling assumptions

Two scenarios were simulated, using the modelling assumptions given in Table 1.

<table>
<thead>
<tr>
<th>Accident parameter</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Scenario</td>
<td>leak of LH$_2$-tank or system in tunnel</td>
<td></td>
</tr>
<tr>
<td>- Hydrogen source</td>
<td>7 kg H$_2$ in 15 min, release rate 7.7 g H$_2$/s</td>
<td>10 kg in 10 min, variable release rate 70 g H$_2$/s</td>
</tr>
<tr>
<td>- Hydrogen distribution</td>
<td>$T_0$ (H$_2$) = 20 K, no tunnel ventilation</td>
<td>$T_0$ (air) = 300 K, $v_0$ (air) = 0</td>
</tr>
<tr>
<td>- Ignition time</td>
<td>at end of H$_2$ release (15 min)</td>
<td>7.5 s after begin of release</td>
</tr>
<tr>
<td>location</td>
<td>at tunnel ceiling (lamp)</td>
<td>at tunnel ceiling</td>
</tr>
</tbody>
</table>

It should be realized that for the given scale of the problem, the investigated hydrogen sources are quite significant. When expressed in terms of equivalent combustion power, the H$_2$-rates correspond to roughly 1 - 10 Mw during the release period of 10-15 minutes.

The assumed tunnel dimensions were 4.5 m height, 9 m width and 200 m length. Constant pressure boundary conditions at the tunnel ends allowed displacement flow of air out of the tunnel after begin of the H$_2$ injection.

The tunnel was partly blocked by standing cars and truck. The simulations were performed with the GASFLOW code [3], using an 8 x 22 x 273 mesh, giving a total of about 48,000 computational cells.
4. Results

4.1 Case 1

In this scenario with a relatively low release rate and a long lasting distribution phase, the hydrogen rises to the tunnel ceiling due to buoyancy forces and spreads over significant distances in both directions. Fig. 1 depicts a cross section through the computed H$_2$-air cloud at the end of the release period (900 s). The regions for upward and downward flame propagation limits are indicated by the 4 and 9 vol.% H$_2$-isosurfaces in space, respectively. Due to the mixing of cold H$_2$-gas with ambient air, a vertical temperature distribution corresponding to the H$_2$-volume fraction develops in the tunnel.

![Fig. 1: Computed hydrogen distribution in the tunnel at the end of the H$_2$-release phase (900 s).](image)

Ignition of the mixture was assumed at the end of the release phase to have the maximum possible combustion energy available. The ignition was triggered at the tunnel ceiling, directly above the release point, using the igniter model of GASFLOW [3]. Fig. 2 shows the distribution of the burned gas (T > 800 K) and of the unburned gas (H$_2$ > 4 vol.%) at different times. The simulation predicts a relatively slow deflagration (< 10 m/s) along the tunnel ceiling, due to the low turbulence level in the upper section of the tunnel. The combustion is incomplete (4 out of 7 kg H$_2$) because in large parts of the cloud hydrogen was diluted below the flammability limit (4 %). The thermal power of the combustion process decays from initially 40 MW down to 4 MW after 30 seconds.

4.2 Case 2

Two sub-cases were analyzed:
2.1: release of 10 kg H$_2$ over 10 minutes without ignition, and
2.2: release with early ignition 7.5 seconds after begin of H$_2$-release.

Case 2.1 investigated the potential for flame acceleration (FA) and deflagration-to-detonation-transition (DDT) which could result from the faster H$_2$-release (> 75 g H$_2$/s) and the larger H$_2$-mass (10 kg), compared to case 1. The applied criteria for flame acceleration and detonation transition were derived from a large new experimental data base with homogeneous H$_2$-air-dilutent mixtures [4]. Because in the present case large H$_2$ concentration gradients exist in the evolving H$_2$-air cloud, different cloud boundaries were used for the evaluation of the criteria (4 % H$_2$, 8 % H$_2$, 16 % H$_2$).

At 200 s these three clouds have reached characteristic dimensions $D = V_{\text{cloud}}^{1/3} = 7.6$ m, 6.2 m and 4.1 m, respectively. The computed criteria data are shown in Fig. 3. Values above one mean that FA and DDT are possible. The data clearly indicate that above the release location an enriched kernel forms in the H$_2$-air cloud, which is sufficiently reactive to support flame acceleration and DDT, provided enough turbulence and confinement exist also. In case 2.2 a continuously active igniter was modelled at the tunnel ceiling above the release point. The edge of the burnable cloud reached the igniter about 7.5 s after begin of the H$_2$-release, starting a standing diffusion flame from thereon. The size of the combustion zone and the gas velocities decrease with decreasing H$_2$-release rate.
Fig. 4 depicts the situation at 20 s.
Fig. 2: Deflagration of extended, partly premixed H$_2$-air cloud in tunnel (case 1), late ignition at 900 s assumed, temperature scale in K.

Three computed fields are shown: gas temperature, H$_2$ volume fraction and gas velocities in the vertical plane through the release point. At this time the H$_2$-release rate amounted to 37 g H$_2$/s, resulting in a thermal power of the flame of about 4.4 MW, of which roughly 10 - 20 % appear as thermal radiation. The used computational grid allows only an approximate representation of the diffusion flame. The continuous H$_2$ burn leads to a stratified temperature and oxygen distribution in the tunnel. The early ignition prevents noticeable pressure loads, but on the other hand creates significant local thermal loads. Secondary burns may be initiated by the standing flame. If necessary, the thermal consequences could be easily mitigated by restricting the possible H$_2$-release rate from the tank to lower values by some design measures.
5. Discussion

In safety assessments the risk contribution $R$ from a given event is often defined as the product of the probability $P$ of occurrence times the resulting consequences $C$ ($R = C \times P$). These topics are discussed in the following sections.

5.1 Consequences

The relevant consequences of $\text{H}_2$-air combustion in the present context are pressure loads, thermal loads and oxygen consumption.
The described numerical simulations have shown that in case of accidental H₂ release in a tunnel the time and the location of the first ignition are the key parameters, determining the combustion process and the resulting consequences.

In case of late ignition, defined here as $t_{\text{ignition}} > t_{\text{release}}$, sufficient time is available for formation of a diluted, stratified and extended H₂-air cloud along the tunnel ceiling. The ignition of this lean cloud, e.g. at the ceiling, leads to a slow and incomplete deflagration without significant pressure generation. In case of early ignition at the ceiling ($t_{\text{ignition}} < t_{\text{release}}$), the flame flashes back to the source and a standing diffusion flame forms at the release location. The flame dimensions are governed by the H₂-source strength ($g \text{H}_2/s$). Pressure development is again negligible.

In both cases significant thermal loads are generated by convection and radiation of burned gases. The total thermal load from the H₂ diffusion flame (case 2) should be less than that from a gasoline burn because of the smaller radiosity of H₂/steam compared to that of hydrocarbon combustion products. Scenarios with late ignition, similar to case 1, lead to new hydrogen specific thermal loads with much larger affected space regions and higher energy release rates (40 MW in case 1), than typical gasoline burns. Compared to the standing diffusion flame the thermal load from the freely propagating flame (case 1) is extended in space but compressed in time (seconds versus minutes).

The third aspect is oxygen availability for evacuation of the tunnel. Due to the high buoyancy of hydrogen a stratified mixture develops in the tunnel and prior to ignition, sufficient oxygen should be available practically everywhere near the ground level. Accidental intrusion of H₂ into the passenger compartment should be prevented by design measures. The calculations have shown that even after ignition a stable stratification remains in the tunnel because the hot combustion products accumulate under the tunnel ceiling. For both cases (early and late ignition) breathable oxygen concentrations are predicted in most parts of the lower half of the tunnel.

The investigated release rates lead to sensitive H₂-air mixtures near the H₂ source which can in principle support fast turbulent deflagrations and detonations. Additional prerequisites are however generation of well premixed H₂-air gas volumes, high turbulence levels and geometrical confinement near the ignition point. The most likely accident scenario for which these conditions could be fulfilled, is ignition of the turbulent H₂-air jet at an intermediate time in or near the damaged car. The mechanistic analysis of such an event would require higher spatial resolution than used here and another code with specific turbulent combustion models (COM3D [5]).

The consequences may be summarized in the following way: For the investigated scenarios the time and the location of the first ignition turned out to be the most influential accident parameters. Early and late ignitions are expected to create mainly thermal loads, intermediate ignitions of well mixed H₂-air regions in confined geometries have potential for fast combustion regimes with high pressure generation. The consequences of the described tunnel accidents could be mitigated, e.g. by restricting the hydrogen mass flow rate from the damaged LH₂-system to the environment.

5.2 Probabilities of ignition

The first ignition occurs when either the edge of the expanding flammable cloud (≥ 4 vol.% H₂) arrives at an active ignition source or when an ignition source becomes active within the burnable cloud. In the assumed accident scenarios a H₂-air cloud rapidly expands within an environment containing many potential ignition sources (hot running engine, electric sparks in or near the collided vehicles). Several m³ of pure H₂ are released during the first 10 seconds. Under such conditions an early ignition ($t_{\text{ign}} < t_{\text{release}}$) is much more likely than a late ignition ($t_{\text{ign}} > t_{\text{release}}$). Early ignition implies that substantial distribution and dilution of the available LH₂ inventory in the tunnel has not yet occurred, and that high H₂ concentrations will be involved in the burn.
5.3 Risk

Combining consequences and ignition probabilities suggests that the risk in tunnel accidents is dominated by sequences with early ignition of locally enriched H₂-air plumes. These can either result in benign standing flames with only thermal loads (above case 2) or in fast combustion modes with negligible thermal but high pressure loads. The latter event path has not been addressed yet because the analysis requires higher spatial resolution, a detailed model of the vehicle geometry and more sophisticated, verified models for turbulent combustion simulation (e.g. [5]).

6. Conclusions

The hydrogen distribution and combustion calculations performed for different accident scenarios have provided new detailed data on shape, size, hydrogen concentrations, gas flow velocities, temperatures and oxygen distributions before and after ignition of the evolving H₂-air cloud. Most important accident parameters are time and location of the first ignition.

Late ignition of the fully released LH₂-inventory, which would result in a large, partly premixed H₂-air cloud under the tunnel ceiling is considered more unlikely. The extent of damage in tunnel accidents is dominated by sequences with early ignition of a locally enriched H₂-air jet or plume near the damaged vehicle. Depending on the ignition location and energy, details of geometry and flow field (confinement, turbulence) the initially quasi-laminar deflagration may or may not develop into a fast turbulent deflagration or detonation. In the first case pressure loads will dominate the consequences, in the second case thermal loads will prevail. Compared to gasoline burns, the pressure loads can be significantly larger, but the thermal loads will be smaller.

Compared to gasoline the use of hydrogen as vehicle fuel has some safety implications which are principally connected with the different physico-chemical properties. They influence the formation of a combustible mixture, the time and location of ignition, the potential for high combustion speeds.

The consequences of tunnel accidents can and should be controlled. Theoretical tools are available to consider all important influence parameters and to investigate the efficiency of various mitigating design measures, aiming at reduced hydrogen concentrations, hydrogen flow rates, smaller premixed H₂-air clouds, combustion speeds, and pressure loads. Such additional analyses seem necessary for the realization of a safe hydrogen based traffic system.

References


