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Simulation of Hydrogen Releases from Fuel-Cell Vehicles in Tunnels

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1 Introduction

An important issue concerning the safe use of hydrogen-powered vehicles is the possibility of accidents inside tunnels resulting in the release of hydrogen. Releases of hydrogen from high-pressure gaseous storage tanks on vehicles are designed to occur only for conditions where a heat source, such as a fire, is present to actuate the thermal pressure relief device (TPRD). It is presumed that this heat source also serves as an ignition source that will immediately burn the released gas and a jet flame will ensue. A highly unlikely scenario is the case where the released hydrogen remains unignited for some period of time followed by a possible ignition.

2 Risk Analysis Considerations

A true risk assessment of this accident scenario would involve a two-part study with a determination of the frequency of occurrence of the specific accident and an evaluation of the severity of the consequence from the incident. In the case of the frequency evaluation, there is no statistical data for hydrogen releases from vehicles and hence any determination of the frequency of occurrence has a high degree of uncertainty. Some data is available for gasoline-powered vehicles in tunnels, and as a first approach it can be assumed that the accident rate for hydrogen vehicles in tunnels might be similar. For a typical road tunnel in a highly populated area there are approximately 35×10^6 vehicle transits per year with approximately 720 crashes per year and only 12 vehicle fires per year (most of which are initiated by mechanical or electrical malfunctions). Based on this data the fraction of tunnel transits resulting in a vehicle fire is approximately 3×10^{-7} fires/transit. Assuming an average vehicle makes between 1 to 100 tunnel transits per year, then the estimated frequency of the vehicle being involved in a tunnel fire would range from 3×10^{-7} /yr to 3×10^{-5} /yr. The estimated fire frequency contribution from vehicle crashes is 2×10^{-6} /yr. Not all tunnel fires involving hydrogen vehicles may induce TPRD activation and subsequent hydrogen ignition. From a risk point of view, the first consideration is that the risk to individuals from hydrogen vehicle accidents in tunnels does not substantially increase their existing risk from everyday life. In the United States the average individual fatality risk from all types of accidents (from everyday life) is approximately 5×10^{-4} /yr (LaChance et al., 2009). Recognizing that only a fraction of hydrogen vehicle fires will result in TPRD releases, hydrogen ignition, and a subsequent fatality, the individual fatality risk from hydrogen vehicle fires in tunnels is estimated to range between 2×10^{-7} /yr to 3×10^{-5} /yr and does not significantly increase the level of individual risk to the public.

3 Consequence Analysis

Because hydrogen vehicle PRDs are thermally activated devices, they would most likely be activated by a fire engulfing the high-pressure hydrogen storage tank, which would serve to ignite the flammable gas upon release. Presumably, ignition of the flammable gas would occur almost instantaneously upon exiting the vent pipe, resulting in a jet flame rather than a deflagration through a premixed hydrogen and air mixture which could result in overpressure. In a scenario involving TPRD activation, flammable gas venting to the environment must be considered and the time delay prior to ignition becomes a parameter. Thus, in performing consequence analysis of a hazardous gas release, which is an important part of risk assessment, knowledge of the time-dependent transport of flammable gas from the vent pipe of a vehicle PRD during the blow-down of the high-pressure tank is important.

Sandia's computational fluid mechanics code, FUEGO (Moen et al., 2002), was used to perform simulations of hydrogen fuel-cell vehicle (HFCV) TPRD releases inside ventilated tunnels. For these simulations, high-pressure hydrogen gas was vented simultaneously from three separate onboard tanks through three separate TPRD vents located on the bottom of the HFCV. The vents were approximately 15cm above the roadway and the hydrogen flow was directed downward. Each tank held approximately 1.67kg of hydrogen at an initial pressure of approximately 70MPa. Predictions of the evolution of flammable hydrogen/air gas volume inside the tunnel resulting from the blowdown were performed by first calculating the steady air flow within the tunnel (and exhaust plenum for a transversely ventilated tunnel) and then releasing the flammable gas into the tunnel air flow through the openings representing the three TPRD vents. The transient nature of the tank blow downs was modeled with the Sandia developed compressible network flow analysis code, NETFLOW (Winters, 2001, 2009), and used to develop transient boundary conditions for the TPRD vents.

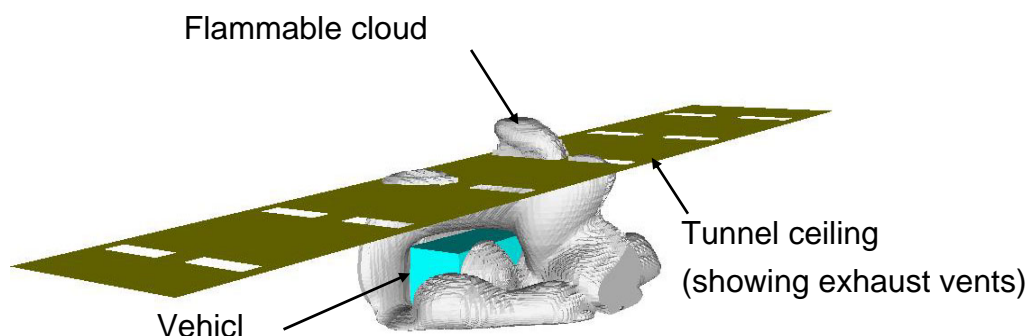


Figure 1: Simulation of flammable hydrogen cloud (4% - 75% mole fraction) around vehicle 2 seconds into three TPRD release in a transversely-ventilated tunnel (ventilation rate of 15 air changes per hr).

Figure 1 shows the evolution of the flammable hydrogen cloud (4% - 75% mole fraction) around the vehicle in a transversely-ventilated tunnel 2 seconds into the 3 TPRD release. Figure 2 shows flammable volumes of hydrogen from the vehicle release for various ventilation rates in a transversely-ventilated tunnel. Results indicate that increasing the

ventilation rate reduces the peak flammable volume and also significantly reduces the time required for dilution below the lower flammability limit (4% mole fraction) of hydrogen.

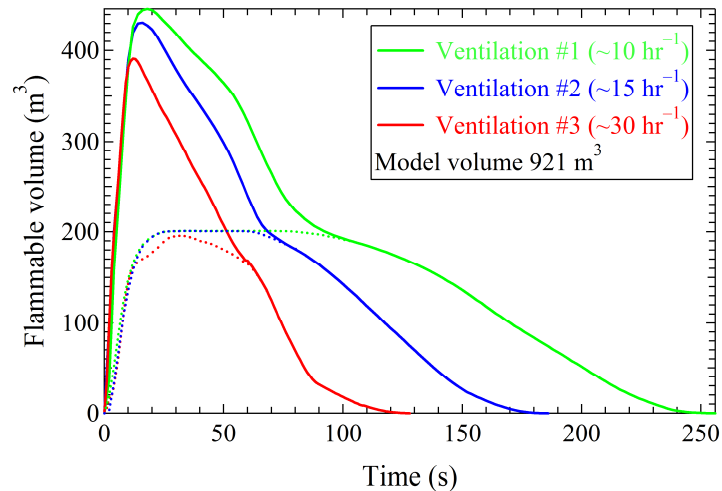


Figure 2: Simulation results showing evolution of flammable hydrogen volume (4% - 75% mole fraction) from a vehicle with three simultaneous TPRD releases in a transversely-ventilated tunnel for ventilation rates of 10, 15, and 30 air changes per hour. Solid lines are total flammable volumes (both tunnel and ventilation plenum) and dashed lines are flammable volumes in plenum only.

Ignition overpressure simulations for the hydrogen vehicle releases in the transversely-ventilated tunnel were also performed. These simulations were based on flammable cloud volumes and concentrations extracted from the FUEGO dispersion calculations under nominal ventilation conditions (15 air changes per hour). A FLACS (2009) model of the transversely-ventilated tunnel and vehicle was developed and three-dimensional concentration distributions of the flammable hydrogen cloud volume were extracted from the FUEGO simulations and read into the FLACS model. FLACS was then used to perform a transient simulation of ignition of the cloud and the associated overpressure generated by a rapid deflagration wave propagating across the cloud. The time delay between the beginning of the TPRD release and ignition and its effect on the deflagration overpressure were also studied. Figure 3 shows simulations of the peak overpressure on the tunnel walls for ignition under the vehicle 2 seconds after the beginning of the TPRD release. Figure 4 shows simulations of the transient variation of the pressure and impulse on the tunnel sidewalls adjacent to the vehicle for the case where ignition occurs 2 seconds after the beginning of the TPRD release. Figure 5 shows the peak ignition overpressures observed in the simulations for different ignition delay times (time between beginning of TPRD release and ignition) and ignition locations.

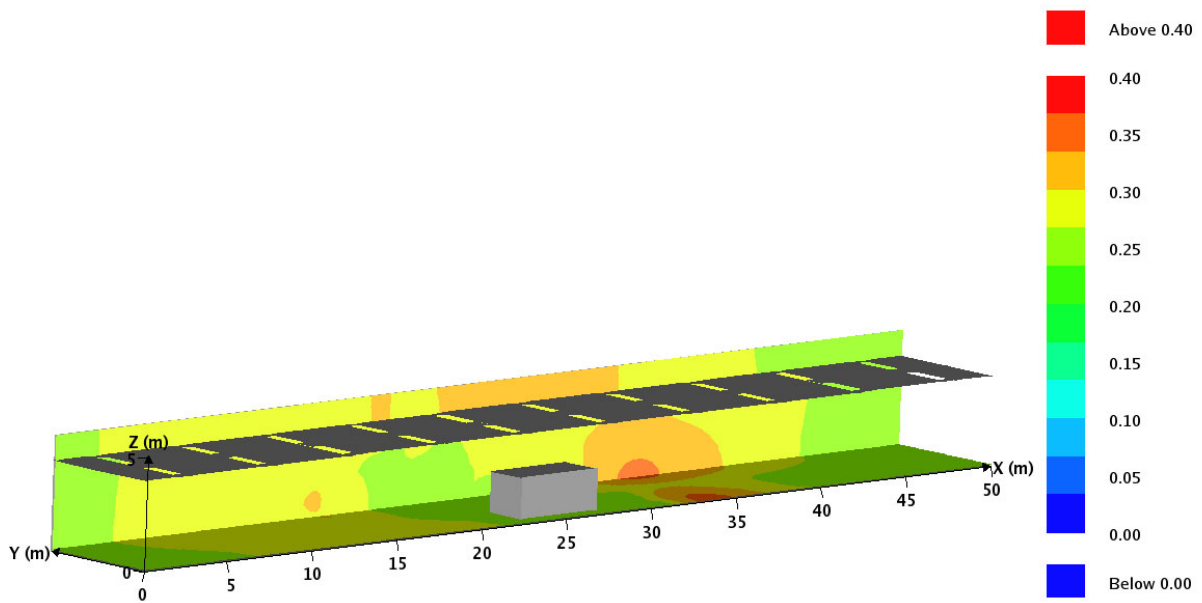


Figure 3: Simulation of peak ignition overpressures (barg) on transversely-ventilated tunnel walls for ignition under the vehicle 2 seconds after the beginning of the TPRD release.

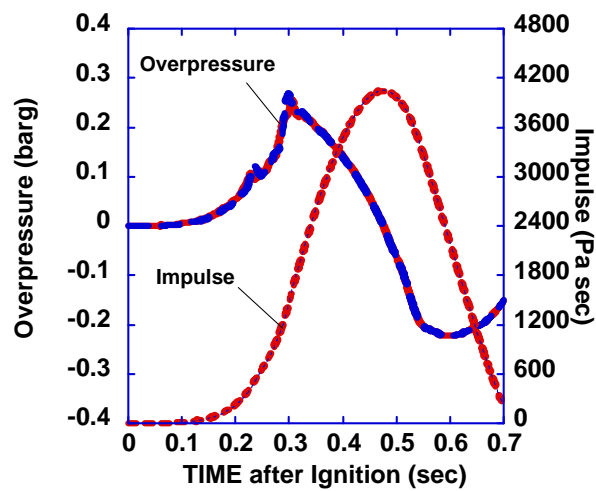


Figure 4: Simulation results showing transient variation of ignition overpressure and impulse on transversely-ventilated tunnel sidewalls (at location of vehicle) for ignition of the hydrogen cloud 2 seconds after the beginning of the TPRD release.

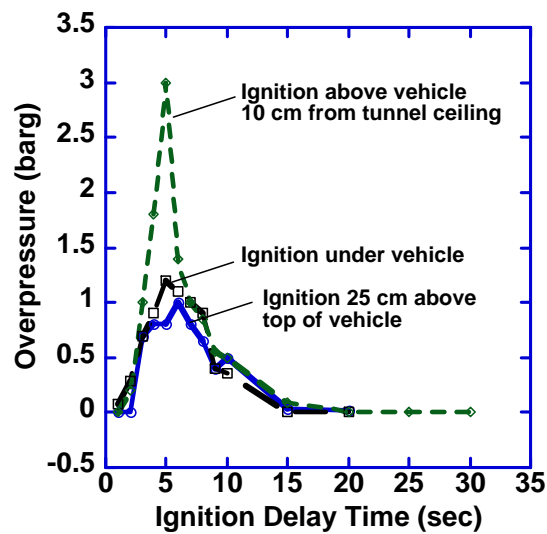


Figure 5: Simulation results showing peak ignition overpressure in the transversely-ventilated tunnel for different ignition delay times (time between beginning of TPRD release and ignition) and locations.

4 Experimental Validation of Model Simulations

A set of experiments was performed in a scaled tunnel test facility at the SRI Corral Hollow Experiment Site (CHES) to provide model validation data for the simulations (see Figure 6). The SRI tunnel test facility has a cross-sectional area that is approximately $1/2.53$ that of the full-scale transversely-ventilated tunnel. As part of these experiments appropriate scaling factors (Hall and Walker, 1997) were determined to create a set of scaled-tunnel tests that resembled as closely as possible the full-scale tunnel simulations. The scaled hydrogen mass released in the test was related to the full-scale hydrogen mass released by the volume ratio $(1/2.53)^3$. The time for the scaled mass release was related to the time for full-scale mass release by using the Froude number and dimensionless time. The initial tank pressure for the experiments was 13.79 MPa and the tank volume was chosen so that it would hold the scaled mass of hydrogen. The release diameter was then designed to match the scaled mass flowrate versus scaled time tank blowdown curve from the full-scale release. Measurements were made of the hydrogen concentration, flame speed, and ignition delay overpressure in the scaled tunnel resulting from the release produced by activation of three simulated PRD vents on the bottom of the scale-model vehicle. As part of the work a FUEGO dispersion model and FLACS deflagration model of the test tunnel and vehicle geometry were developed. These models were used prior to the tests to estimate the placement of concentration and pressure sensors in the tunnel test geometry and to determine the amount of expected overpressure from ignition of the hydrogen releases. Figure 7 shows a simulation of the flammable hydrogen cloud (4% to 75% mole fraction) in the SRI test tunnel one second after the beginning of the release. Pretest FLACS ignition deflagration simulations of the test tunnel geometry using three-dimensional concentration maps from the FUEGO dispersion simulations indicated that the maximum overpressure would be approximately 0.5 barg and that a peak in the overpressure would occur with increasing ignition delay time as observed in the full-scale tunnel simulations (see Figure 5). Figure 8

shows a comparison of the peak overpressures observed in the experiment for different ignition delay times as compared to the FUEGO/FLACS model simulations. The ignition overpressure simulations are found to be in good agreement with the experimental data.



Figure 6: Photograph and cross-sectional area sketch of scaled tunnel and vehicle at SRI Corral Hollow Experiment Site (CHES).

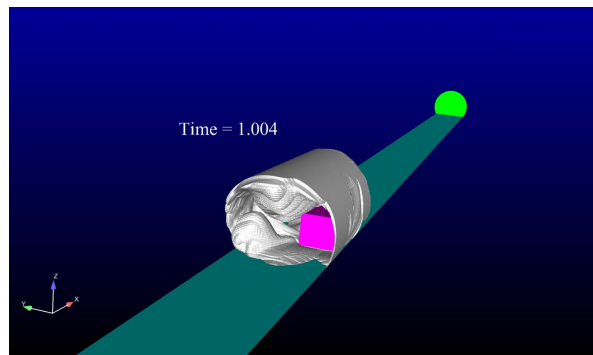


Figure 7: Simulation of flammable hydrogen cloud volume (4% to 75% mole fraction H₂) around the vehicle in the SRI test tunnel one second after the beginning of the release.

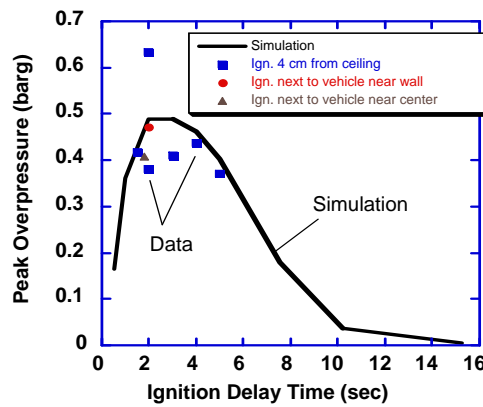


Figure 8: Comparison of measured peak ignition overpressure in the SRI test tunnel facility with results from FUEGO/FLACS model simulations.

Figure 9 shows predicted and measured hydrogen mole fraction at two locations within the scaled tunnel at the tunnel ceiling. Both predicted and measured hydrogen mole fraction increase rapidly from 0 to approximately 0.4 within 1 second of the start of the release at 1.5 m along the tunnel axis from the center of the vehicle (red curve and symbols). At approximately 2 seconds after the start of the release the predicted and measured hydrogen mole fraction increase from 0 to approximately 0.3 at 3.0 m from the center of the vehicle along the tunnel axis (black curve and symbols). Qualitatively the predicted and measured values agree and the concentration behavior is expected. At larger distances from the release, there is a longer delay before the detection of hydrogen and the magnitude of the hydrogen mole fraction is reduced due to dispersion. The agreement between predicted and measured values is reasonable.

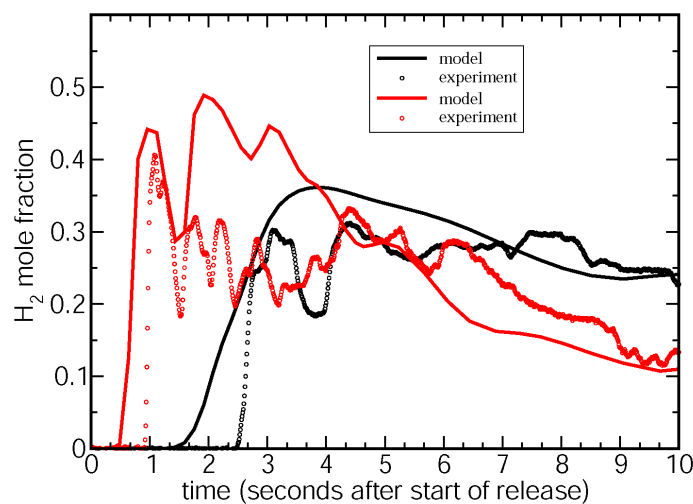


Figure 9: Comparison of time evolution of predicted and measured H₂ mole fraction at two locations on the centerline at the ceiling in the scaled tunnel: red curve and circles 1.5 m from vehicle center; black curve and circles 3.0 m from vehicle center.

5 Summary and Conclusions

Simulation results for a hydrogen fuel-cell vehicle in a full-scale tunnel have been performed for the case where hydrogen gas is vented from the vehicle as a result of thermal activation of the pressure relief device (PRD). The same modeling approach used in the full-scale tunnel modeling was validated in a scaled model by comparing simulated results with measured results from a series of scaled-tunnel test experiments performed at the SRI Corral Hollow test facility. Results of the simulations were found to be in good agreement with the experimental data. Finally, a rudimentary risk analysis indicated that the level of potential risk from hydrogen vehicles accidents involving thermally activated PRDs in tunnels does not appear to significantly increase the current level of individual risk to the public from everyday life.

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