ANALYSIS OF TRANSIENT HYDROGEN RELEASE, DISPERSION AND EXPLOSION IN A TUNNEL WITH FUEL CELL VEHICLES USING ALL-SPEED CFD CODE GASFLOW-MPI

Yabing Li[1], Jianjun Xiao[*,1], Han Zhang[1], Wolfgang Breitung[2], Jack Travis[2], Mike Kuznetsov[1], Thomas Jordan[1]

[1]Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
[2]GFX-Global GmbH, 76297 Stutensee, Germany

*Contact: jianjun.xiao@kit.edu

ABSTRACT

Hydrogen energy is expanding world wide in recent years, while hydrogen safety issues have drawn considerable attention. It is widely accepted that accidental hydrogen release in an open air environment will disperse quickly, hence not causing significant hydrogen hazards. A hydrogen hazard is more likely to occur when hydrogen is accidentally released in a confined place, i.e. parking garages and tunnels. Prediction the consequences of hydrogen detonation is important for hydrogen safety assessment, and for ensuring the safety of installations during accidents. Hence, an accident scenario of hydrogen release and detonation in a tunnel is analysed with GASFLOW-MPI in this paper. GASFLOW-MPI is a well validated parallel CFD code focusing on hydrogen transport, combustion and detonation. GASFLOW-MPI solves compressible Navier-Stokes equations with a powerful all-speed Arbitrary-Lagrangian-Eulerian (ALE) method, hence it can cover both the non-compressible flow during the hydrogen relesase and dispersion phases, and the compressible flow during combustion and detonation. A 3D model of a tunnel including eight cars is modelled. Firstly, the hydrogen dispersion in the tunnel is calculated. Then the detonation in the tunnel is calculated by manually igniting the hydrogen at the top of the tunnel when the λ criterion is maximum. The pressure loads are calculated to evaluate the consequence of the hazard.

1.0 INTRODUCTOIN

As the development of technology for hydrogen fuel cell vehicles (HFCV) evolves, it's clear that this form of transportation will become increasingly popular in the future. In reaching that goal, the impact of HFCV's on different road structures must be considered. Among those, a key issue is tunnels[1] because hydrogen could be released and then confined, possibly leading to a severe hazard. A literature survey shows that the most possible scenario is the opening of the Thermal Pressure Relief Devices (TPRD) during a tunnel accident. The TPRD is designed to open at high temperatures to protect the hydrogen tank. In this situation, a combusting hydrogen jet is most likely developed by opening the TPRD, causing thermal loads to the surrounding structures.

There is a Large body of research regarding the safety of hydrogen vehicles in tunnels, both experimentally and numerically [2–6]. For example, the HyTunnel project was established to extend knowledge and development safety procedures using both experimental and numerical studies [7]. Most current numerical simulations are concerned with hydrogen release, dispersion and combustion. While considering the large amount of hydrogen released in a short time, we are focusing on the most severe scenario in this paper, which is hydrogen ignition several seconds after the TPRD opens. A detonatable hydrogen cloud will form in the tunnel before ignition in this situation. A detonation event will cause high pressure loads to the surrounding vehicles and human beings in those vehicles.

Therefore, a tunnel accident scenario including hydrogen release, dispersion and detonation for HFCV's is analysed in this paper. The geometry model consists of a actual scaled tunnel and several, as shown in Fig. 1. GASFLOW-MPI calculates the hydrogen release and dispersion in the tunnel to obtain the initial condition for the ensuing detonation simulation. Th detonation is calculated by igniting the hydrogen cloud near the ceiling. Propagation of the blast wave is calculated to evaluate it's impact on the surroundings.

2.0 GASFLOW-MPI

The parallel CFD computational fluid dynamics code GASFLOW-MPI is well validated and widely used for analyses regarding hydrogen dispersion, combustion and detonation. GASFLOW-MPI uses a robust Implicit Continuous Eulerian-Arbitrary Lagrangian-Eulerian solution algorithm (ICE'd ALE) to solve compressible Navier-Stokes equations; hence, the code is validated for all-speed flows. GAFLOW-MPI is thoroughly validated for combustion and detonation simulations with several experimental data; for instance,, turbulent combustion of premixed H_2-air mixture in the ENACCEF facility, H_2 jet firse in a vented combustion chamber, and hydrogen-air detonation in a hemispherical balloon located in the open atmosphere. Detailed information for these validation studies can be found in reference [8].

3.0 MODELING OF THE TUNNEL

The geometry information for the cross section of the tunnel is given in Fig. 2 (a) [5]. The actual model consists eight cars placed in two lanes in the tunnel as shown in Fig. 1. Each of the cars located att the centre of each lane with a spacing distance of 1.3m between cars to simulate a tight traffic condition. The hydrogen injection location is at the rear of the second car, venting towards the tunnel ceiling which is the most severe scenario based on the reference [1]. The mass flow rate injection given in Fig. 2 (b) is equivalent to the flow rate when three TPRDs open within a hydrogen fuel cell car (70MPa)[1,9]. The computational region is given with a length of 12m, width of 9.6m, and height of 6.6m as shown in Fig. 3, and is divided into 130*80*120 = 1,248,000 computational volumes. The mesh is refined with minimum size of 0.04m at the injection location and at the tunnel ceiling. The maximum computation volume is progressively stretched to 0.2m. The mesh in the y-direction is refined by doubling before ignition to better resolve the detonation, with total mesh of 130*160*120 = 2,496,000 computational volumes. None-reflecting boundary conditions are imposed at both ends of the tunnel. The Detached eddy Simulation model [10] is adopted for the hydrogen dispersion phase and a one-step global chemical kinetics model is adopted for the combustion. Heat losses are neglected for the detonation calculation because the time-scales are usually large compared with the blast wave speed.

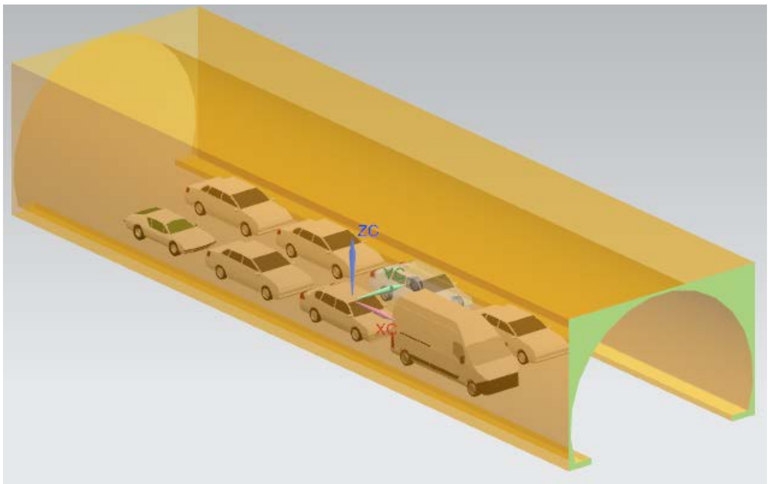
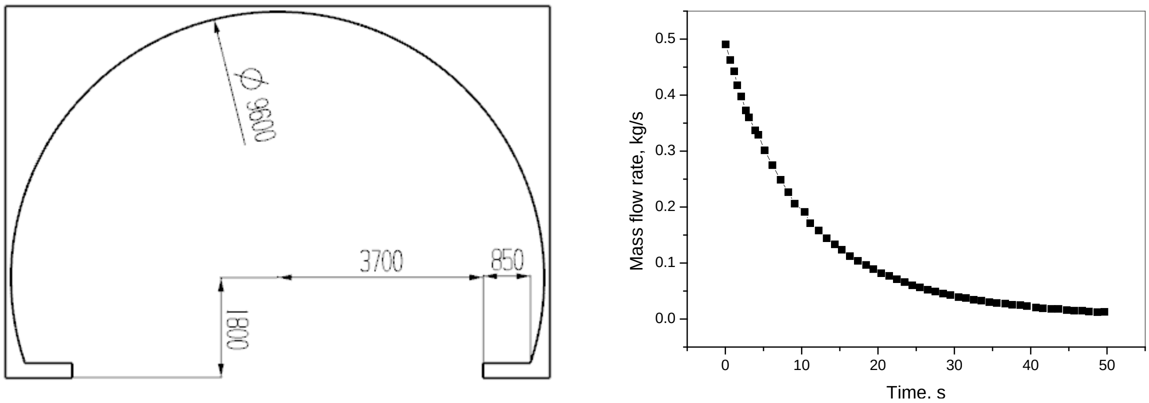
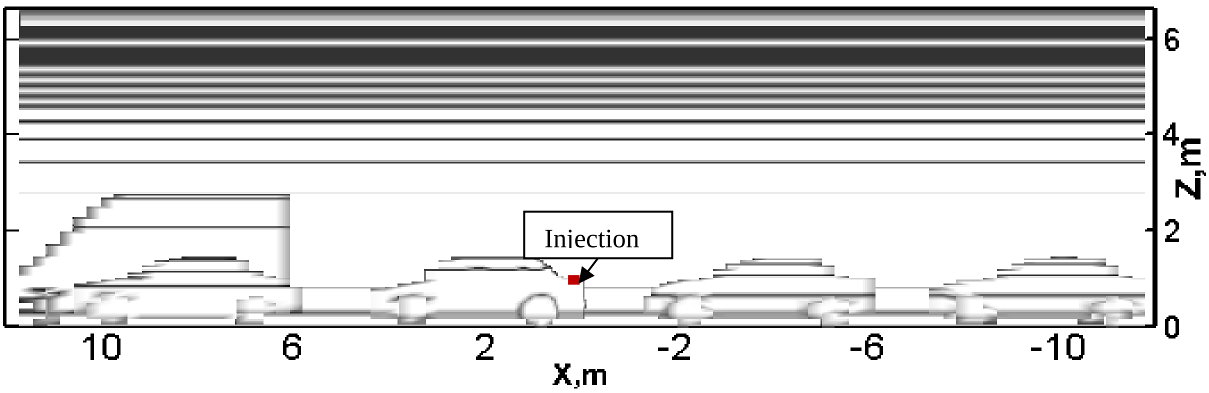


Figure 1. Diagram of the geometry model

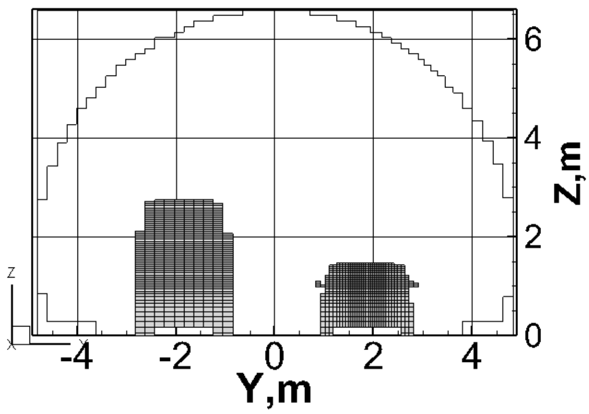


(a) Cross-section of the tunnel (b) Mass flow rate of the injection

Figure 2. Cross-section of the Tunnel and the flow rate in the injection

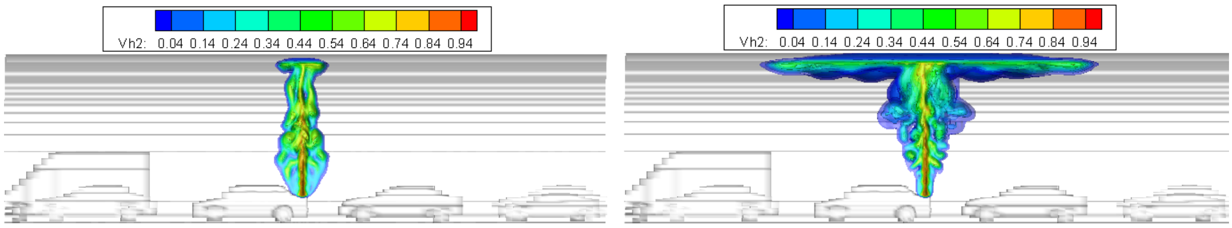


(a) Cross-section along the centerline of the injection

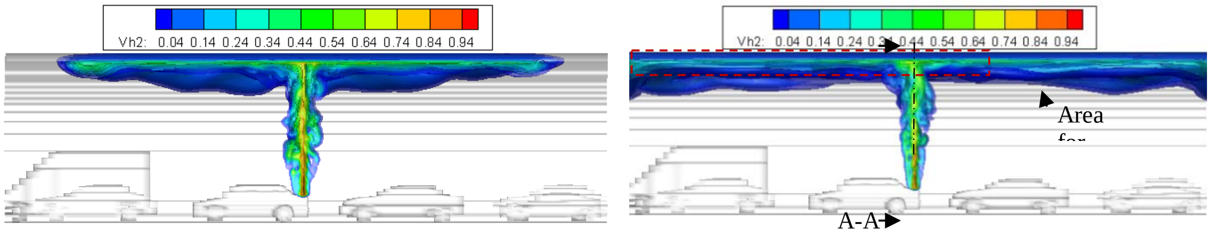


(b) Left view of the computational region

Figure 3. Diagram of the computational region



(a) 1s (b) 4s



(c) 8s (d) 16s

Figure 4. Distribution of hydrogen cloud (>4%) - the x-z cut at the injection

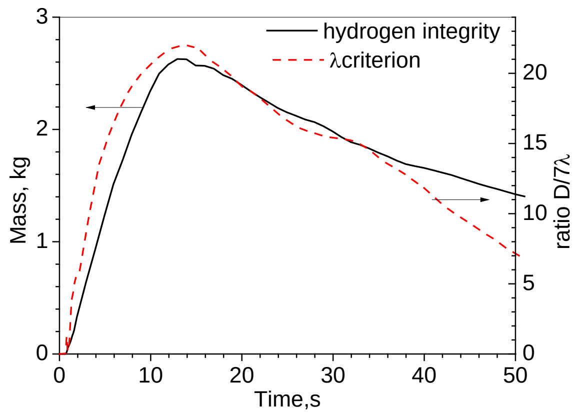


Figure 5. hydrogen integrity and λ criterion in the area

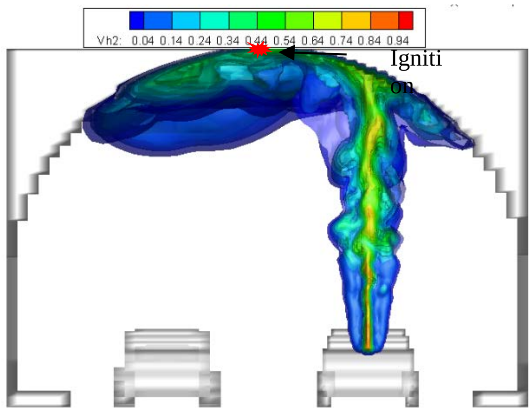


Figure 6. A-A view of hydrogen concentration and the location of ignition

4.0 RESULT AND DISCUSSION

4.1 Hydrogen release and distribution in the tunnel

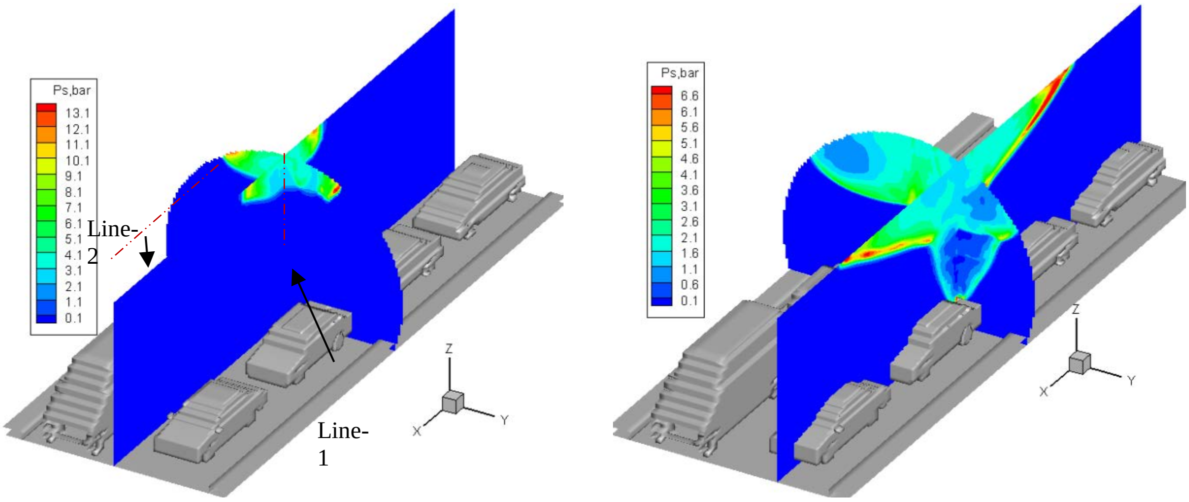
Hydrogen is released upward in the tunnel, and accumulates at the tunnel ceiling due to the density difference between hydrogen and air. Fig. 4 shows the flammable hydrogen cloud (H_2 vol >4%) in the tunnel at different times. The hydrogen cloud is blocked at ceiling and is pushed sidewises along the tunnel by the continuous hydrogen jet. Hence a layer of combustible hydrogen with thickness 0.5-0.6m is formed at the tunnel ceiling. The hydrogen concentration has a strong vertical gradient with the maximum hydrogen concentration near the ceiling around 40% decreasing to 0% at the bottom of the layer. We take the region of the hydrogen layer (0.6m below the ceiling) to evaluate the hydrogen risk. The hydrogen integrity and the averaged λ criterion of this region is given in Fig. 5. The hydrogen integrity increases at first, then decreases as the injection rate decreases and the as the hydrogen cloud is pushed out of the computational region. The maximum λ criterion is reached at 16 s, then decreases as the hydrogen integrity decreasing. We ignite the hydrogen layer at 16s considering conservation, at this time, the hydrogen integrity is 2.5 kg at this area, and is around 3.5 kg in the entire computational region. The location of ignition is shown in the A-A view of the hydrogen concentration in Fig. 6.

4.2 Hydrogen detonation in the tunnel

The mesh in the y-axis direction is refined by doubling the number of computational volumes for the detonation simulation and the initial condition is shown in Fig. 4 (d) and Fig. 6. A contour plot of the overpressure (in bar) in the tunnel is shown in Fig. 7. The viewing angles and elevation cuts are different in Fig. 7 (a) to (d) to demonstrate characteristics at different times. The maximum overpressure reaches a value of 8 bars at the front of the blast pressure wave as shown in Fig. 7 (a), and remains that value as the pressure propagates. While the pressure decays as the wave propagates into the non-combustible, the pressure along the tunnel centreline decays less than 2 bars at the bottom of the tunnel. Behaviour is different when the blast pressure reaches the hydrogen injection location. The hydrogen mixes with the surrounding air as the jet forming a detonable cloud in the shape of a cone, which is hollow inside because there is insufficient oxygen in the cone centre to support combustion. As a result, the pressure contour shows a vertical cone above the injection location, as shown in Fig. 7 (b). The over pressure is between 7-8 bar in this region, which is sufficiently high to overturn a car according to the reference [11]. This cone-shaped wave superposed on the original blast wave creates an overpressure peak value of 3 bar as shown in Fig. 7 (c). Meanwhile, the front of the pressure wave reaches the first adjacent cars in the first row, with an overpressure of 3.1 bar. The superinposed pressure peak reaches the adjacent side cars shown in Fig. 7 (d). In the meantime, the pressure wave propagating from the ceiling hits the third-row of cars with overpressures of around 2-3 bars.

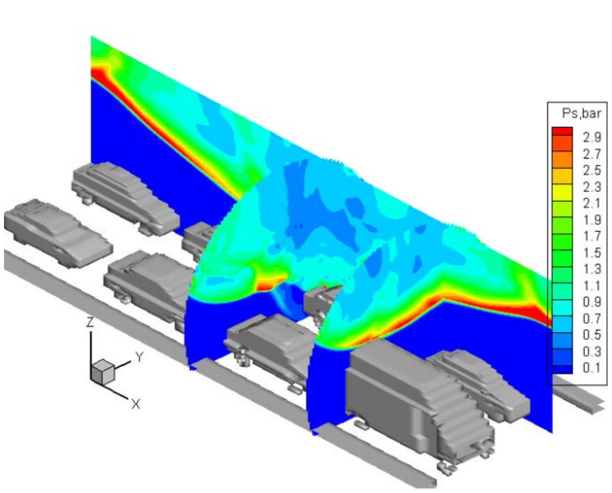
The transient overpressure profiles from the ignition, along axis Line-1 and Line-2, are shown in Fig. 7 (a) and in Fig. 8 (a) and (b), respectively. The overpressure along Line-1 is around 5 bar but decays along the z-axis direction, while increasing along the line Z=3.64m, because of the supeinrposed wave shown in Fig. 7 (b). This pressure value is significantly higher than the experiment with a similar amount of hydrogen, where the overpressure is of the order ~10^2 kPa. [2]. This is because the hydrogen layer beneath the ceiling forms a semi-confined layer. The former experiment conducted on a flat semi-confined hydrogen layer shows overpressure at the order of ~10^0 bar [12].

The blast pressure wave propagates much faster along the lengthwise direction than that of the vertical direction due to fact that the gas mixture is none combustible below the hydrogen laye. It takes 5.1ms for the pressure wave to propagate from the ignition location to the edge of computational region (Line-2), while it takes 7.2ms to propagate to the height of the injection (Line-1), as shown in Fig. 8. The speed of pressure wave propagation is of the order 10^3 m/s along the lengthwise direction, as opposed to 600-800m/s in the vertical direction. Along the injection centreline, it takes only 2 ms for the pressure wave to reach the ceiling(distance = 4.58m) due to the high concentration of the hydrogen jet, with the wave speed of the order of 10^3 m/s.

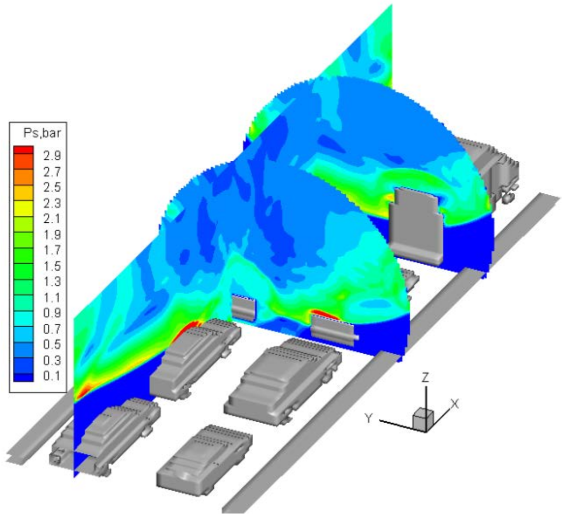


(a) 2ms (x-z view at tunnel centerline and y-z view at injection centerline)

(b) 4ms (x-z view y-z view at injection centerline)

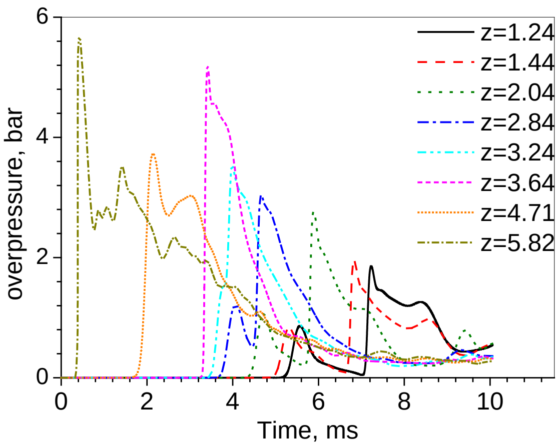


(c) 7ms (x-z view, y-z view at injection centreline and y-z view of the first-row cars)

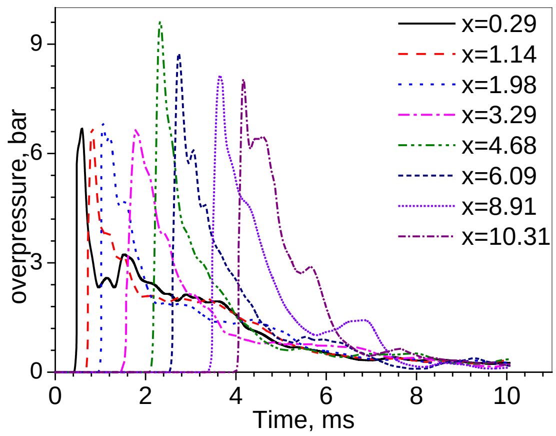


(d) 9ms (x-z view, y-z view at injection centreline and y-z view of the first-row cars)

Figure 7. Contour of overpressure in the tunnel



(a) Along Line-1



(b) Along Line-2

Figure 8. transient profiles of overpressures

5.0 CONCLUSIONS

The transient hydrogen release, dispersion and detonation in a tunnel for fuel cell vehicles is analyzed using the parallel CFD code GASFLOW-MPI in this paper. The following conclusions can be drawn:

(1) Hydrogen accumulates beneath the ceiling, forming a thin layer with strong concentration gradients.

(2) Igniting the hydrogen layer generates a blast wave with overpressure of the order ~ 8 bars, and propagates in the tunnel. The wave speed is about ~10^3m/s when the wave propagates in the burnable hydrogen cloud, decaying to around 600-800m/s in the unburnable region.

(3) The pressure wave propagates through the detonatable hydrogen cloud forming a reversed-cone-shaped wave before reachingthe HFCV after the ignition, with the overpressure about 8 bars. The blast wave propagates into the unburnable air at a lower speed showing an impact on the surrounding cars with a lower overpressure.

In future studies we will evaluate the damage due to this detonation event for both vehicles and human beings using P-I diagrams. Since it is possible the hydrogen be ignited immediately after release, further studies will focus on the jet fire and the thermal loads to surroundings.

REFERENCE

1. Lafleur C, Bran-Anleu G, Muna AB, Ehrhart BD, Blaylock M, Houf WG. Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study. SAND2017-11157,Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550; 2017.
2. Breitung W, Bielert U., Necker G., Veser A., Numerical Simulation And Safety Evaluation Of Tunnel Accidents With A Hydrogen Powered Vehicle, 13th World Hydrogen Energy Conference, Beijing, China, June 12 – 15, 2000
3. Groethe M, Merilo E, Colton J, Chiba S, Sato Y, Iwabuchi H. Large-scale hydrogen deflagrations and detonations. Int J Hydrogen Energy. 2007;32(13):2125–33.
4. Baraldi D, Kotchourko A, Lelyakin A, Yanez J, Middha P, Hansen OR, et al. An inter-comparison exercise on CFD model capabilities to simulate hydrogen deflagrations in a tunnel. Int J Hydrogen Energy. 2009;34(18):7862–72.
5. Venetsanos AG, Baraldi D, Adams P, Heggem PS, Wilkening H. CFD modelling of hydrogen release, dispersion and combustion for automotive scenarios. J Loss Prev Process Ind. 2008;21(2):162–84.
6. Molkov V, Verbecke F, Makarov D. LES of hydrogen-air deflagrations in a 78.5-m tunnel. Combust Sci Technol. 2008;180(5):796–808.
7. Kumar S, Miles SD, Adams P, Kotchourko A, Hedley D, Middha P. Hytunnel project to investigate the use of Hydrogen Vehicles in Road Tunnels. In: International Conference on Hydrogen Safety (ICHS3). Ajaccio, Corsica, France, 16-18 September 2009; 2009.
8. Xiao J, Breitung W, Kuznetsov M, Zhang H, Travis JR, Redlinger R, et al. GASFLOW-MPI: A new 3-D parallel all-speed CFD code for turbulent dispersion and combustion simulations. Int J Hydrogen Energy. 2017;42(12):8346–68.
9. Middha P, Hansen OR. CFD simulation study to investigate the risk from hydrogen vehicles in tunnels. Int J Hydrogen Energy. 2009;34(14):5875–86.
10. Zhang H, Li Y, Xiao J, Jordan T. Detached Eddy Simulation of hydrogen turbulent dispersion in nuclear containment compartment using GASFLOW-MPI. Int J Hydrogen Energy. 2018;43(29):13659–75.
11. Baker WE, Cox PA, Kulesz JJ, Strehlow RA, Westine PS. Explosion hazards and evaluation. Vol. 5. Elsevier; 2012.
12. Kuznetsov M, Yanez J, Grune J, Friedrich A, Jordan T. Hydrogen combustion in a flat semi-confined layer with respect to the Fukushima Daiichi accident. Nucl Eng Des. 2015;286(June 2013):36–48.