COMPARISONS OF HAZARD DISTANCES AND ACCIDENT DURATIONS BETWEEN HYDROGEN VEHICLES AND CNG VEHICLES

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ABSTRACT

For the emerging hydrogen-powered vehicles, the safety concern is one of the most important barriers for their further development and commercialization. The safety of commercial natural gas vehicles has been well accepted and the total number of natural gas vehicles operating worldwide was approximately 23 million by November 2016. Hydrogen vehicles would be more acceptable for the general public if their safety is comparable to that of commercialized CNG vehicles. A comparison study is conducted to reveal the differences of hazard distances and accident durations between hydrogen vehicles and CNG vehicles during a representative accident in an open environment. The tank blowdown time for hydrogen and CNG are calculated separately to compare the accident durations. CFD simulations for real world situations are performed to study the hazard distances from impinging jet fires under vehicle. Results show that the release duration for CNG vehicle is over two times longer than that for hydrogen vehicle, indicating that CNG vehicle jet fire accident is more time-consuming and firefighters have to wait a longer time before they can safely approach the vehicle. For both hydrogen vehicle and CNG vehicle, the longest hazard distance near the ground occur about 1 to 4 seconds after the initiation of the thermally-activated pressure relief devices. Afterwards the flames will shrink and the hazard distances will decrease. For firefighters with bunker gear, they must stand 6 m and 14 m away from the hydrogen vehicle and CNG vehicle, respectively. For general public, a perimeter of 12 m and 29 m should be set around the accident scene for hydrogen vehicle and CNG vehicle, respectively.

1.0 INTRODUCTION

Commercial natural gas vehicles have become more and more popular in the general public, just like the well-accepted conventional vehicles such as gasoline and diesel vehicles. The number of natural gas vehicles has increased rapidly in the last two decades, according to NGV Statistics Summary data (Fig. 1) [1]. There were approximately 23 million natural gas vehicles operating worldwide by November 2016 and the total number is expected to exceed 30 million by 2024.

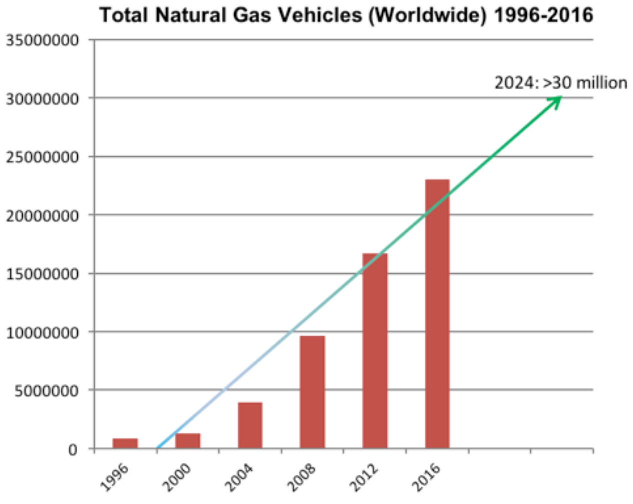

Figure 1. The number of NGVs in the last two decades [1]

In the meantime, a new type of more environment-friendly vehicle comes to the vehicle market and attracts public attention: the hydrogen fuel cell vehicles. However for the emerging hydrogen vehicles, the safety concern is one of the most important barriers for their further development and commercialization.

Like most of natural gas cars that stored the fuel in high pressurized condition, the hydrogen in fuel cell cars are also mostly stored in the form of compressed gas, but at higher pressure. Furthermore, compared with natural gas, hydrogen gas has wider flammability range, lower ignition energy and higher burning rate. These unique properties of hydrogen raise safety concerns, and consumers may ask a simple question: whether the hydrogen cars are as safe as the natural gas cars. This paper will try to answer this question by comparing the fuel release consequences of the two types of cars during typical accidents.

2.0 TYPICAL ACCIDENT

Both hydrogen and methane are stored onboard at high pressures. All vehicular high-pressure gaseous storage systems are required to be equipped with thermally-activated pressure relief device (TPRD). Normally if the temperature reaches more than 110 centigrade, the TPRD will be activated and the contents of the container will be released rapidly. This safety device will significantly reduce the risk of tank catastrophic rupture by venting the excess pressure outside. However, the released flammable gas could raise additional safety problems if being ignited.

The flammable gas release from TPRD can be considered as a typical incident as the system is designed to do so. Such incident is mostly likely to occur in an event of a car fire. A car fire can be caused by a variety of reasons such as a fire following a road collision accident, a battery fire or autoignition due to strong sunlight exposure, etc. When the fire causes the temperature around TPRD going up to 110 centigrade, the TPRD will be triggered and then release the flammable gas. The gas will be ignited immediately in the fire environment and causes jet fire impinging on the ground and spreading flame outwards, as TPRDs are commonly located under the vehicle, orientating the release downwards. The downward degree is usually 45 degree for methane vehicle and vertically downward for hydrogen vehicle.

3.0 MODELING

3.1 Vehicle and Environment Parameters

The car is assumed to be parked in the open and the onboard high pressure tank is assumed to be at full capacity, in order to investigate the worst case scenario. Hydrogen and methane storage parameters are selected from the specification of the Honda Clarity [2] and Honda Civic [3], respectively. They are comparable to each other because of the similar driving range. One is approximately 240 miles and the other is 225-250 miles. Detail parameters are shown in table 1. The ambient pressure and temperature are assumed to be 1 atm and 20 °C, respectively. There is no wind in the study.

Table 1. Hydrogen and methane storage parameters applied in the study.

Name	Fuel type	Mileage (mile)	Pressure (MPa)	Inventory
Honda Clarity	H_2	240	35	4 kg
Honda Civic	CNG	225-250	25	20 kg

The car geometry is a typical sedan with dimensions of 5.16 m long, 1.83 m width and 1.47 m height, as shown in Fig. 2. The TPRD is assumed to be located near the rear wheel under the vehicle as shown in Fig. 2, and its orifice diameter is 4.2 mm, according to Tamura's experiment [4].

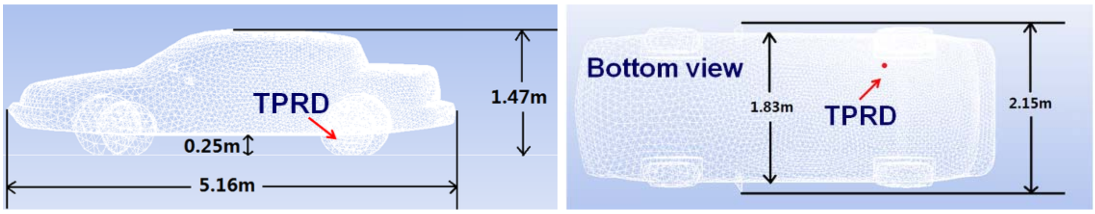

Figure 2. Geometry of the sedan and location of TPRD.

3.2 Blowdown Model

Releases from high pressures of either 25 MPa or 35 MPa are under-expanded jets, where the pressure at the exit of the nozzle is above atmospheric pressure. Calculation of this expansion with complex shock structure from the nozzle exit to the Mach disk requires intensive computation. In many practical situations, it is not necessary to fully resolve these shock structures if the main concern is not the near field around the nozzle. For the determination of hazard distance for gas releases, the far field parameters are the major concern. Therefore, it is convenient for our study to substitute the under-expanded jet with an expanded one by applying the notional nozzle model that was introduced by Molkov et al. [5].

In real world conditions, a release from a high pressure tank is not a steady release but a blowdown process with pressure dropping in the reservoir until the tank is empty. The notional nozzle model can be applied to simulate pressure dynamics in the storage tank during an underexpanded jet release and to calculate the blowdown time. If we define the density (ρ), temperature (*T*), pressure (*P*) and velocity (*V*) in the reservoir, at the nozzle orifice and at the notional nozzle as shown in Fig. 3, the calculation procedure can be described as below.

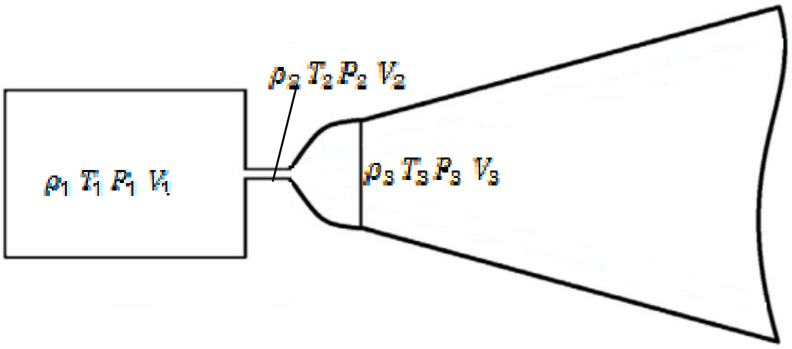

Figure 3. State parameters in blowdown calculation.

The density in the reservoir from the Abel-Nobel equation of state is calculated as

$$\rho_1 = P_1 / ZR_{H2}T_1 \, . \tag{1}$$

The transcendental equation of isentropic expansion to find density at the orifice is solved as

$$\left(\frac{\rho_1}{(1-b\rho_1)}\right)^{\gamma} = \left(\frac{\rho_2}{(1-b\rho_2)}\right)^{\gamma}\left[1+\frac{(\gamma-1)}{2(1-b\rho_2)^2}\right]^{\frac{\gamma}{\gamma-1}} \tag{2}$$

The relationship below is used to find temperature T_2 and speed of sound V_2 at the orifice

$$T_1/T_2 = 1 + (\gamma - 1)/2(1 - b\rho_2)^2 \tag{3}$$

$$V_2^2 = \gamma R_{H2} T_2 /(1 - b\rho_2)^2 \tag{4}$$

T_3 at the notional nozzle is calculated by using energy conservation:

$$T_3 = \frac{2T_2}{(\gamma+1)} + \frac{(\gamma-1)}{(\gamma+1)} \frac{P_2}{\rho_2(1-b\rho_2)R_{H2}} \tag{5}$$

Then, gas density at the notional nozzle can be calculated with P_3 equal to the ambient pressure as well as the sonic velocity V_3. Finally, the continuity equation is used to get D_3 at the notional nozzle,

$$D_3 = D_2 \sqrt{C_D \frac{\rho_2 V_2}{\rho_3 V_3}} \tag{6}$$

And mass flow rate is determined as

$$\dot{m} = \rho_3\ V_3 \pi {D_3}^2/4 \tag{7}$$

Once specifying a time step, one will obtain the mass released within the time step, and the mass left in the reservoir which can be used to update a new density in the reservoir. Then the above procedures can be repeated over and over again.

3.3 CFD Modelling

During tank blowdown, the notional nozzle diameter will decrease with the dropping of pressure in the reservoir. It would be difficult to change the effective diameter during a CFD transient calculation. Instead, mass inflow can be treated as volumetric sources of mass, momentum, and energy in order to avoid having to constantly alter the effective diameter with the passing of time during the simulation. Using this approach the volumetric sources can equivalently reflect the changing parameters at the notional nozzle. This approach was validated against HSL experimental data [6] of hydrogen releases through a 3 mm diameter orifice. The results reveal that if the volumetric source size is smaller than 4 times of the notional nozzle diameter then concentration decay in under-expanded jets is reproduced accurately.

Considering the viscous model implemented, the shear-stress transport (SST) k-ω model was applied in the turbulence calculations performed, as this model is known to allow for a more accurate near wall treatment than k-ε model. The SST k-ω model was developed by Menter [7] to effectively blend the robust and accurate formulation of the k-ω model in the near-wall region with the freestream independence of the k-ε model in the far field. For combustion modelling the eddy-dissipation model is applied. It is a turbulence-chemistry interaction model based on the work of Magnussen and Hjertager [8]. In this model, reaction rates are assumed to be controlled by the turbulence, so expensive Arrhenius chemical kinetic calculations can be avoided. The model is computationally cheap and effective for one or two step heat-release mechanisms.

The calculation domain is a rectangular cuboid with dimensions of L x W x H = 50 x 40 x 30 m. As for boundary conditions, the ground and the car surface are set as wall boundaries and other boundaries are set as pressure outlets. Simulations are carried out using ANSYS Fluent.

3.4 Harm Criteria

The harm criteria for the determination of hazard distances are listed in table 2. Two temperature limits are adopted as harm criteria for different vulnerable targets. For the general public, a temperature of 70 °C is taken as an acceptance criterion for no harm. For the firefighters with thermal protective clothing, it is conservatively assumed that they should not work in an environment where the temperature is higher than 260 °C, as the bunker gear is designed not to ignite, melt, drip, or separate when exposed to such temperatures for five minutes[9]. It should be noted that the harm effects near the ground are defined as adverse effects under a height of two metres above the ground.

Table 2. Harm criteria for jet fires from TPRD under a car.

Vulnerable targets	Ignited releases
General public	70 °C
Firefighters with bunker gear	260 °C

4.0 RESULTS AND DISCUSSIONS

4.1. Accident Durations

In an open air, hazard associated with releases of hydrogen or methane will be self-eliminated once the tank blowdown completes because both gases are lighter than air and will be not likely stay near the ground. Therefore the tank blowdown time can represent the accident durations. The tank blowdown from TPRD of hydrogen vehicle and CNG vehicle are shown in Fig. 4 below. The tank blowdown time for hydrogen vehicle is about 120 seconds, while the tank blowdown time for CNG vehicle is about 260 seconds. The TPRD release accident duration for CNG vehicle is over two times longer than that for hydrogen vehicle, indicating that CNG vehicle jet fire accident is more time-consuming and firefighters have to wait longer time before they safely approach the vehicle.

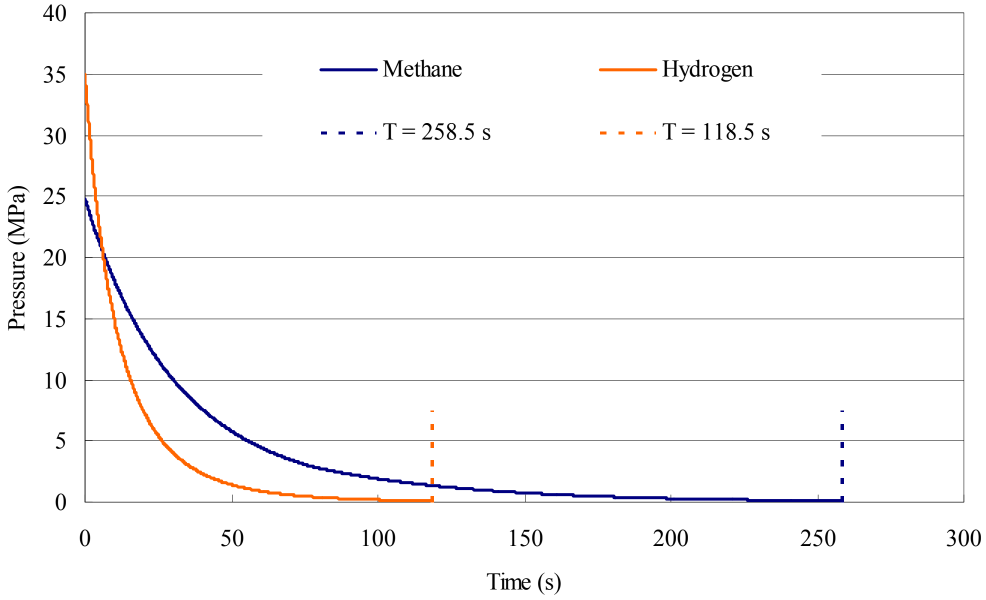

Figure 4. Pressure drop during tank blowdown.

4.2 Hazard Distances

It can be seen from Fig 5 that the longest flame length is about 5.2 m (the left image) and 11.3 m (the middle image) for hydrogen vehicle and CNG vehicle, respectively. The current CNG vehicle produces flame length more than two times longer than that of current hydrogen vehicle. One reason is the CNG vehicle release direction is 45 degree backward so more momentum on the horizontal direction leads to longer flame length. The other reason is that methane is heavier than hydrogen and vertically downward methane release will lead to a flame length of 6.8 m (the right image), longer than the flame length of hydrogen. For both hydrogen and methane releases, the largest flame near the ground occurs about 1-3 seconds after the initiation of the TPRD. Afterwards, the flames will shrink and the hazard distances will decrease.

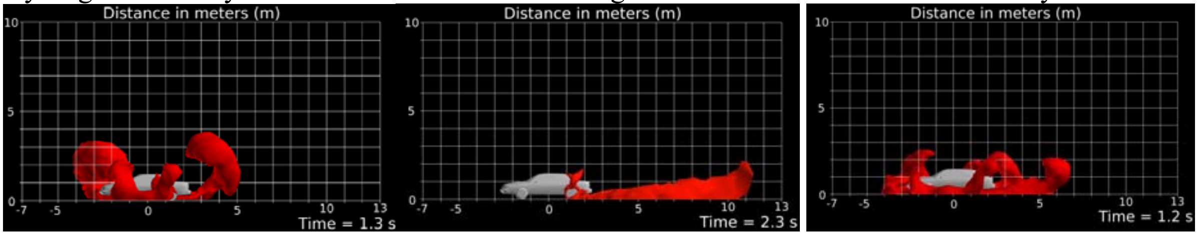
Hydrogen vertically downward Methane 45 degree backward Methane vertically downward

Figure 5. Snapshot of largest flame envelopes

It can be seen from Fig. 6 that the longest distance of 260 centigrade envelope can reach about 5.5 m (the left image) and 13.5 m (the middle image) for hydrogen vehicle and CNG vehicle, respectively. The harm distance produced by current CNG vehicle is more than two times longer than that produced by current hydrogen vehicle. This indicates that the firefighters with bunker gear must stand 6 m and 14 m away from the hydrogen vehicle and CNG vehicle, respectively.

For both cases the longest harm distances near the ground occur about 1-3 seconds after the initiation of the TPRD. Afterwards, the high-temperature envelope will shrink and the hazard distances will decrease.

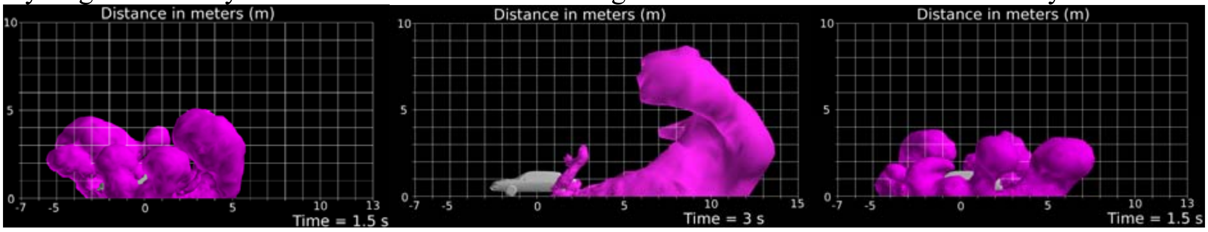
Hydrogen vertically downward Methane 45 degree backward Methane vertically downward

Figure 6. Snapshot of largest temperature envelope at 260 °C

It can be seen from Fig. 7 that the longest distance of 70 centigrade envelope can reach about 6.1 m (the left image) and 14.3 m (the middle image) for hydrogen vehicle and CNG vehicle, respectively. The current CNG vehicle produces "no harm distance" more than two times longer than that of current hydrogen vehicle. If we apply a safety factor of 2, then a perimeter of 12 m and 29 m for the general public should be set around the accident scene for hydrogen vehicle and CNG vehicle, respectively

For both cases the longest hazard distance near the ground occur about 1-4 seconds after the initiation of the TPRD. Afterwards, the hazard distances will decrease.

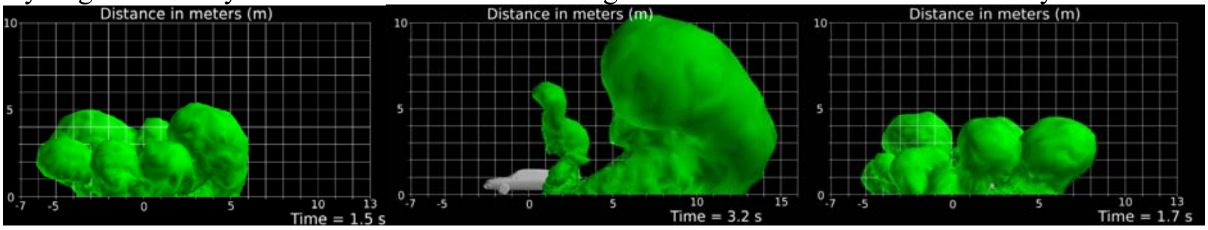
Hydrogen vertically downward Methane 45 degree backward Methane vertically downward

Figure 7. Snapshot of largest temperature envelope at 70 °C

5.0 CONCLUSIONS

This paper investigates the accident durations and hazard distances for gas releases from TPRD of onboard storage. A comparison study is conducted for hydrogen vehicle and methane vehicle at approximately the same mileage. Results from the analysis are summarized below:

(1) The TPRD release accident duration for CNG vehicle is over two times longer than that for hydrogen vehicle, indicating that CNG vehicle jet fire accident is more time-consuming and firefighters have to wait for longer time before they safely approach the vehicle.

(2) For both hydrogen vehicle and CNG vehicle, the longest hazard distance near the ground occurs about 1-4 seconds after the initiation of the TPRD. Afterwards, the flame will shrink and the hazard distances will decrease.

(3) For firefighters with bunker gear, they must stand 6 m and 14 m away from the hydrogen vehicle and CNG vehicle, respectively. For general public, a perimeter of 12 m and 29 m should be set around the accident scene for hydrogen vehicle and CNG vehicle, respectively.

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REFERENCES

1. NGV Global's Natural Gas Vehicle Statistics Summary (updated on 12 March 2017), http://www.iangv.org/stats/NGV_Global_Stats1.htm.
2. Honda FCX Specifications, http://www.hondaclarity.org/.
3. Honda civic specifications, http://www.hondacertified.com/certified-pre-owned/civic-natural-gas/.
4. Tamura, Y., Takabayashi, M. and Takeuchi, M., The Spread of Fire from Adjoining Vehicles to A Hydrogen Fuel Cell Vehicle, *International Journal of Hydrogen Energy*, No.39, 2014, pp. 6169-6175.
5. Molkov, V., Makarov, D. and Bragin, M., Physics and Modelling of Underexpanded Jets and Hydrogen Dispersion in Atmosphere, *Russian Academy of Sciences*, 2009, pp. 146-149.
6. Roberts, P.T., Shirvill, L.C., Roberts, T.A., Butler, C.J. and Royle, M.., Dispersion of Hydrogen from High-pressure Sources, Proceedings of Hazards XIX Conference, Symp. Series No.151, Manchester, 28-30 March 2006, pp. 410-421.
7. Menter, F. R., Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications, *AIAA Journal*, 8, No. 32, 1994, pp.1598-1605.
8. Magnussen, B. F. and Hjertager, B. H., On Mathematical Models of Turbulent Combustion with Special Emphasis on Soot Formation and Combustion, 16th Symp. (Int.) on Combustion, Pittsburgh, PA, The Combustion Inst., 1976, pp. 711-729.
9. National Fire Prevention Association, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting, 2007, Boston, Massachusetts.