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Enclosure Safety in a Case of Hydrogen, CNG, or LNG Accidental Release from a Bus Tank

Dorota Brzezińska, Janusz Januszewski

Lodz University of Technology, Faculty of Process and Environmental Engineering
dorota.brzezinska@p.lodz.pl, janusz.januszewski@dokt.p.lodz.pl

Hydrogen, CNG and LNG are highly explosive gases, which can create extremely hazardous conditions if released into an enclosure. The gases' behaviour was checked under accidental release conditions by CFD simulations. It has been proved that too large a gas release diameter orifice could create a dangerous situation, and a gas concentration level above the lower explosive limit, even before emergency ventilation activation. The suggested practical solution for the hazard mitigation could be a limitation of the gas installation diameters fitted on the buses.

1. Introduction

New fuels industry development makes hydrogen and natural gas ideal for large-sized vehicles, like buses, which are more and more popular with the general public, due to their impressive potential as a source of energy with minimal environmental impact. The gases are seen as clean and as ecological fuels, which are mainly produced from renewable sources (Kaplan and Kopacz, 2020). They create new opportunities in the fuel market, together with difficult new challenges in the field of safety, mostly associated with enclosed garages or tunnels. It is reported that the increasing usage of alternative fuels in vehicles (electricity, hydrogen, LNG, LPG etc.) has significantly altered vehicle fire characteristics (Klassen and Ph, 2020). For example, hydrogen ignition energy is ten times lower than methane, and its flame velocity is eight times higher than that of methane (Kaplan and Kopacz, 2020). Also, lower explosive limits (LEL) of H_2 and CH_4, volumetric fractions equal 4% and 4.4%, respectively, are much lower than other flammable gases. Consequently, ensuring a safe infrastructure for such vehicles becomes an urgent goal. This goal could be reached by doing research on the gases' dispersive, burning, and explosive phenomenon and protective measures mitigating hazards relative to gas-fuelled buses (Brzezińska, 2019).

It was found that the release of gas fuel from the onboard storage tank could be a major risk, especially when initiated by an external fire. Such accidents could create different hazardous outcomes and are dependent on varying factors. The most dangerous of which, are situations where the release happens in an enclosed space, such as a garage. In such an instance, the most influenced elements would be, the enclosure volume, its ventilation, and hydrogen release rate (Molkov, 2012a), (Brennan, Makarov and Molkov, 2009), (Molkov, Shentsov and Quintiere, 2014), (Molkov *et al.*, 2014).

In the case of accidental gas release from the bus's fuel tank installation, several scenarios are possible (Dorofeev, 2007), (Hajji, Bouteraa, *et al.*, 2015), (Prasad, Pitts and Yang, 2011), (Brzezińska, Dziubiński and Markowski, 2017), and these can be captured in an event tree, as shown in Figure 1. As an initiating event, the release of the gas fuel from the bus's system was taken into account, with ten different outcomes considered (Brennan and Molkov, 2013). The first possible scenario is its permeation through the tank walls; however, this phenomenon is prolonged and happens mainly in vehicles fuelled with liquid hydrogen, which is not popular (Molkov, 2012a). Another scenario could be the fuel release from the bus's pipe installation, when the tank is closed by a safety valve. In this case, the gas spread could be much more rapid than previously thought possible, but its volume would be limited to the capacity of the pipe installation. The third scenario, which is taken into account most often in accidental gas fuel release analyses, is the gas spread directly from a tank through a thermally activated pressure relief device (TPRD), an obligatory element of the bus's installation (Makarov,

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Shentsov, *et al.*, 2018). This is also the most dangerous scenario and could happen in a case of the TPRD failure or a matter of fire, when the tank pressure increases due to surrounding temperature increase (Molkov, V.; Shentsov, 2016), (Rodionov, Wilkening and Moretto, 2011).

The consequences of the scenarios described above could have different levels of severity, that mostly depend on, ignition sources existing in the enclosure, detection, and ventilation systems. The most dangerous outcome event possible could be a gas explosion, which could comprise of, a deflagration, detonation, or detonation-to-deflagration transition (DDT) (Molkov, 2012b), (Makarov, Hooker, *et al.*, 2018), (Molkov and Bragin, 2015). This scenario could happen, when the gas cloud created in an enclosure, is in a concentration of at least above the lower explosive limit (LEL), at the same time a viable ignition source appears (Saffers and Molkov, 2014), (Najjar, 2013). This can occur when a ventilation system does not work (is not efficient enough/doesn't exist/was not activated by detection system or its activation is too late) (Molkov, 2012a). This phenomenon is investigated in this paper. Another outcome event presented in the event tree (Figure 1) is the gas cumulation in the enclosure, which could also be the cause of another severe event. However, the most probable final event would be a slow gas spread outside of the enclosure. The next event, which is gas dilution and/or evacuation, doesn't create dangerous situations in the enclosure and would happen when the protective measures, such as detection and ventilation system would be sufficiently effective, and/or the hydrogen release would not be sufficiently rapid enough (Weiner, 2014), (Hajji, Jouini, *et al.*, 2015), (Tolias *et al.*, 2019), (Brzezińska, 2021). Finally, one more severe outcome event to consider, would be a pressure peaking phenomenon (PPP), and this happens in enclosers under intensive lighter gas emission into a heavier gas, under minor ventilation conditions (Makarov, Shentsov, *et al.*, 2018), (Molkov and Bragin, 2015), (Lach, Gaathaug and Vaagsaether, 2020). This scenario could be considered, especially in the case of hydrogen-fuelled vehicles, but because it happens very rarely, it is not investigated here.

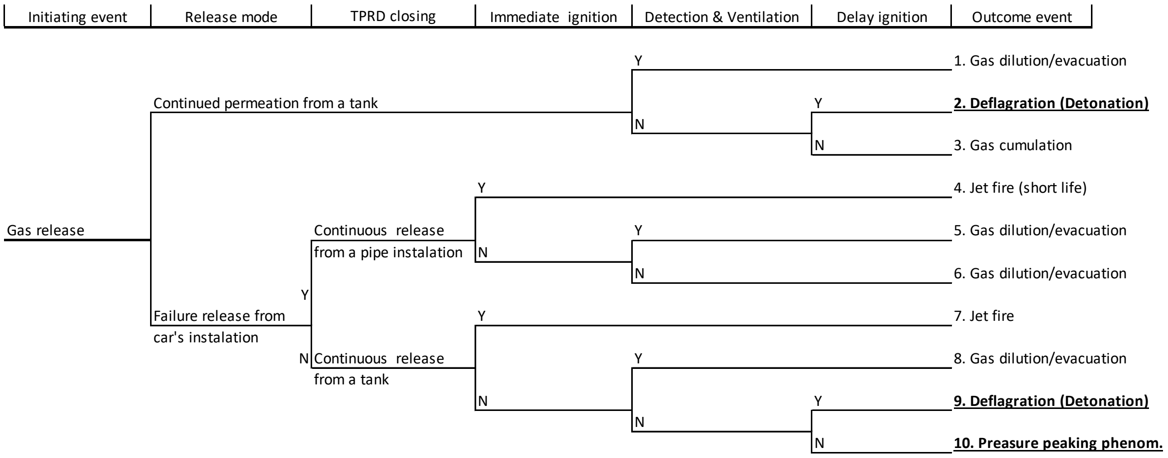

Figure 1. Event tree of gas fuel release accidental scenarios.

The event tree in Figure 1 demonstrates how important and effective detection and ventilation systems would be in a case of a flammable gas release. But looking at this protective system in depth, it appears that its effectiveness could be inadequate if additional conditions are not realised, demonstrated by CFD simulation results of hydrogen and natural gas dispersion, within a confined space, under typical bus tanks release variations. The analyses confirm differences in explosive hazards in the case of hydrogen, CNG, or LNG release, in dependence on the tank orifice diameter, and proves that keeping the gas concentration in an enclosure below the lower explosive limit (LEL) by the time the ventilation system would be activated, could technically be possible if the release quantity is limited. This release limitation can be realized by using pipes in the gas installations with reduced diameters.

The article also demonstrates how the gas dispersion phenomenon in an enclosure depends on, the gas type, tank pressure, and the orifice diameter, and in consequence – there are changes to the buoyancy-induced momentum and the diffusive motions ratio. The expected hydrogen and natural gas behaviour was projected by the Mach (*M*), Reynolds (*Re*), and Froude (*Fr*) numbers, which values predict its flow regimes (Brzezińska, 2021). The flow chart in Figure 2 presents subsequent steps of the analyses.

Figure 2. The analysis steps.

2. The release regimes analysis

Therefore, theoretical verification of the gas dispersion phenomenon could be realized on the basis of three familiar dimensionless numbers analysis: Mach (*M*), Reynolds (*Re*), and Froud (*Fr*), which in many publications are used for gas plume characterization (Krishnapisharody and Irons, 2013), (Fischer *et al.*, 2013). The first step was a definition of the release regimes by the Mach and Reynolds numbers calculations. Where it was assumed that transition from laminar (buoyancy-controlled) diffusion jet to turbulent (momentum-controlled) starts to occur at Reynolds number of around Re = 2000, and choked sonic release are when M≥1 (Molkov and Saffers, 2013), (Prasad, 2014). The Mach and Reynolds numbers were calculated on the basis of equations (1) and (2), respectively (Andrzejewski *et al.*, 2019). The Froud number indicated the influence of gravity on fluid motion, and this was used to evaluate how much buoyancy force affects hydrogen dispersion (Molkov, 2012a). The Fr~1 could mean an absence of the buoyancy effect and a lack of the diffusive distribution of the gas. The Froud number was calculated on the base of equation (3) (Molkov, 2012a).

The basic gases' and bus tanks' parameters are presented in Table 1.

$$M = \frac{U}{a} \tag{1}$$

$$Re = \frac{\rho_0 U D}{\mu} \tag{2}$$

$$Fr = \frac{U^{2}}{gD} \tag{3}$$

The main differences between the tanks are their internal pressure and the difference in the specific gravity of the gases causing significant differences in their capacity. The significant differences in velocity at the orifices appear due to the different pressures. The calculated Reynolds, Mach, and Froud number values are presented in Table 2.

Table 1. The gases' and tanks' parameters.

Gas	*P*	*Vol*	*Mass*	*LEL*
H_2	350	0.312	7.5	4% vol (3,41x10^{-3} kg/m^3)
CNG	200	0.375	42.5	4.4% vol (2,88x10^{-2} kg/m^3)
LNG	15	0.750	345.0	4.4% vol (2,88x10^{-2} kg/m^3)

Table 2. Reynolds, Mach, and Froud number values for the accidental releases.

No	Gas	*V*	*U*	*D*	ρ_0	μ	*M*	*Re*	*Fr*
S1	H_2	0.080	252.39	1.00x10^{-3}	0.08x10^0	8.35	3.65x10^3	1.22x10^7	1.57x10^{14}
S2	CNG	0.017	129.78		0.80x10^0	10.43	7.95x10^1	2.08x10^6	7.47x10^{10}
S3	LNG	2.695	26.59		4.50x10^8	10.43	2.24x10^1	3.29x10^8	5.93x10^9
S4	H_2	0.077	5.34	6.00x10^{-3}	0.08x10^0	8.35	9.76x10^1	1.96x10^6	1.88x10^{10}
S5	CNG	0.650	2.75		0.80x10^0	10.43	8.45x10^1	1.32x10^7	1.40x10^{10}
S6	LNG	0.013	0.56		4.50x10^8	10.43	3.00x10^{-3}	2.65x10^5	1.78x10^1

The Mach number calculations confirmed that only one of the presented scenarios (S6) would be realized in the subsonic regime (M<1). All the other scenarios represent transonic frow regimes (M>1), especially scenario S1, where M=3,650. At the same time, all the release scenarios appeared to create strongly turbulent, momentum-dominated jests (Re>2000). The received Froud numbers confirm their downward trend in subsequent scenarios (around one in order of magnitude), the relevance of which is confirmed by the decreased turbulency. The presented results confirm that, together with the release velocity decreasing, all of the dimensionless numbers decrease also.

3. CFD simulations

Based on the scenarios prescribed above, CFD simulations with the FDS 6 code were prepared. All the simulations were prepared in 3D model of the enclosure, using the software FDS, created by NIST (McGrattan *et al.*, 2019).

The scenarios assumed that the gases were released in a hall room of 10.6 m high and an area of 500 m^2 (a volume of 5,300 m^3). The hall security system provided for individual gas detectors and emergency ventilation with a capacity of 12 air volumes per hour. Ventilation started automatically, 40 s after the gas detection. The aim of the study was to analyse the conditions of gas propagation in the event of their emergency release in the hall space before starting emergency ventilation. The level of LEL condensation is presented in pictures in black to make it easier to understand them.

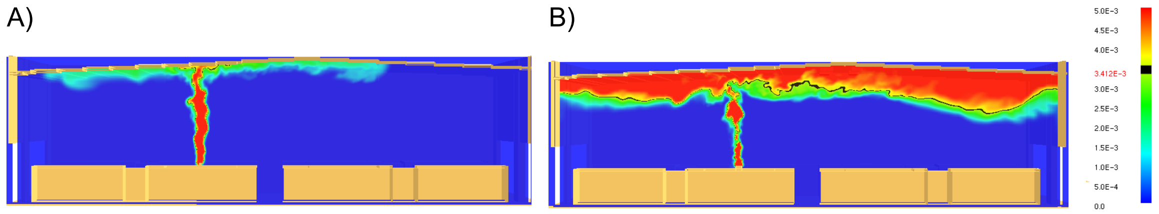

Figure 3. Hydrogen release; A) 1 mm opening; B) 6 mm opening; t=40 s.

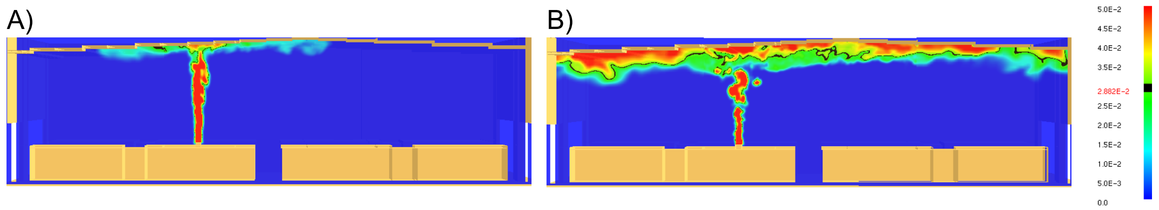

Figure 4. CNG release; A) 1 mm opening; B) 6 mm opening; t=40 s.

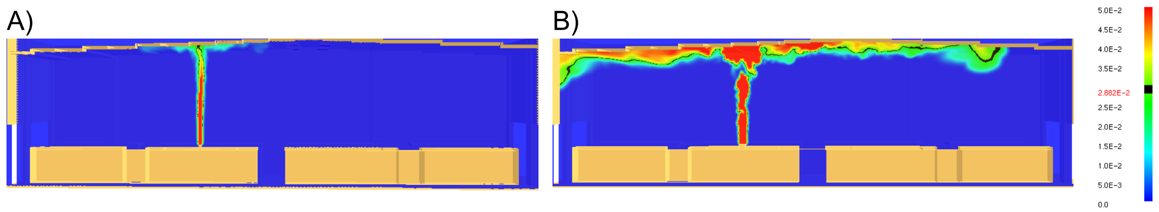

Figure 5. LNG release; A) 1 mm opening; B) 6 mm opening; t=40 s.

After this time, the emergency ventilation was expected to be activated. Presented simulation results demonstrate the differences in the analysed H2, CNG, and LNG gases distribution in the enclosure, depending on the opening release diameter, within 40 s from the damaged bus installation. It is visible that in the case of 1 mm opening diameter, all the gases reached the ceiling, but their condensation doesn't reach the LEL. In contrast, the 6 mm diameter opening causes a high exceedance of the LEL, mostly in the case of hydrogen release. These observations suggest that the orifice diameter could be a significantly important parameter in the explosive enclosures safety considerations in the event of the accidental release of flammable gases. The proposed solution of the identified hazard limitation could be the implementing of an obligatory limitation of the buses' gas installations diameters to the indicated safe level.

4. Conclusions

Hydrogen, CNG, and LNG gases were analysed under accidental release conditions. Six scenarios of bus gas fuels dispersion in a nominally closed space were undertaken. Mach, Reynolds, and Froud numbers calculation allowed for indicative regimes of the released jets. The results confirm a significant influence on the hydrogen dispersion release rate is down to the orifice diameter, and it has been proven that too large a gas outflow could create a dangerous situation, and that a gas concentration above LEL could appear before the emergency ventilation can activate. The suggested solution could be an implementation of an obligatory limitation of the bus gas installation diameters. The observations presented in the article are important in practice for the design of protective measures against hydrogen explosions.

Nomenclature

D – outflow diameter (m),
g - gravitational acceleration (9.81 m/s^2),
$Mass$ – gas mass in the tank (kg),
LEL – lower explosive limit (% vol, kg/m^3),
P – pressure in the tank (bar),
U - velocity at the orifice (m/s),
V - release outflow (kg/s),
Vol – tank volume (m^3),
a - speed of sound (340.30 m/s),
ρ_0 – gas density (kg/m^3),
μ– dynamic gas viscosity (μPa·s).

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