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Influence of ventilation system effectiveness on the safety of hydrogen storage and transportation

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Abstract

In this paper influence of ventilation system availability and effectiveness is evaluated by applying standardized analytical methods for classification of areas of explosive atmospheres with the aim to obtain high dilution for non-hazardous zone or to reduce Zone 2 area within hydrogen storage room and transportation pipeline corridors in industrial applications. Several leakage cross section areas are taken into consideration from 0.025 mm^2 at flanges with compressed fiber and spiral wound gasket, 0.25 mm^2 at ring type joint connections up to 1 mm^2 at small bore connections. Hydrogen storage pressures were varied from typical spherical tank at 50 bar to vertical tube storage at 100 bar. In this case the release rate of gas from a container or pipeline is with choked gas velocity - sonic releases case. Dimensionless discharge coefficient that accounts for the turbulence and viscosity is typically from 0.50 to 0.75. Safety factor was varied from 0.5 to 1, due to uncertainty related to lower flammability limit (LFL) because of possibility of existence of hydrogen background concentrations. Grade of release as estimated as secondary leakage due to a seal rupture. In the case of a pressure of 100 bar and an opening diameter of 0.25 mm^2, the air velocity due to the operation of the ventilation system should be at least 6 m/s, which can be achieved by the proper selection of the ventilation system in a closed space. In all other cases considered in the paper, except for the leakage cross section of 1 mm^2, calculated ventilation air speeds are lower, so conventional ventilation systems (such as mechanical supply and extraction ventilation or local extraction ventilation) can be applied in order to prevent hydrogen explosive atmospheres.

Keywords: hydrogen; storage; trasnsportation; explosive gas atmospheres; ventilation

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1. Introduction

More accessible, efficient and sustainable, fuels are needed in order to reduce environmental footprint of energy production. One of such promising fuels is green hydrogen produced by renewable energy sources. Storage and transportation of hydrogen is the most challenging in terms of explosion risk and safety. The hazards associated with the use of hydrogen can be characterized as physiological (frostbite, respiratory ailment, and asphyxiation), physical (phase changes, component failures, and embrittlement), and chemical (ignition and burning). A combination of hazards occur in most instances. The primary hazard associated with any form of hydrogen is inadvertently producing a flammable or detonable mixture, leading to a fire or detonation. Safety will be improved when the designers and operational personnel are aware of the specific hazards associated with the handling and use of hydrogen.

This topic has been an interest of many researchers, which applied several different methods to access influence of ventilation on formation of explosive atmospheres in hydrogen applications. Generally, the approach to this problem and applied methods can be analytical and numerical. Authors Lee and Lee (2016) analysed appropriate ventilation rate within the housing of the power generating facility of the fuel cell by using the standardized methods given in IEC 60079-10: 2007. It was assumed that the hydrogen storage tanks stored 100 kg of hydrogen at 7 bar and 40°C and that the actual possible size of the leakage holes was 1 mm and 5 mm. They concluded that high ventilation can immediately decrease the actual density from the leakage source, and by lowering the gas density to below lower explosive limit (LEL), high ventilation decreases the range of the risk area to a level small enough to be insignificant. On the other hand, with inadequate effective ventilation the area can become a risk factor for other accidents. Brennan and Molkov (2013) performed analytical study for residential garages of different volumes (from 18 to 46 m^3), to investigate the relationship between pressure relief device diameter, ventilation system performance, and volume for releases in enclosures with a single vent from on board hydrogen storage tanks of 1, 5 and 13 kg at 350 and 700 bar. The release is assumed to occur in a garage with a vent, which size was varied. The results are presented in the form of simple to use engineering nomograms. The authors' conclusion is that further research is needed to develop safety strategies and engineering solutions to tackle the problem of fire resistance of on board storage tanks. Also they suggest that regulation, codes and standards in the field should address this issue

Matsuura et al. (2012) investigated real-time sensing-based risk-mitigation control of hydrogen dispersion and accumulation in a partially open space with dimensions of 2.9×1.22×0.74m, with low-height openings by forced ventilation. Through parametric numerical simulations of the hydrogen exhaust after leakage ceases, authors clarify the effects of the parameters on the rate of exhaust flow from the roof vent and the amount of hydrogen accumulating near the roof, which were critical for ventilation performance.

Papanikolaou et al. (2011) carried out Computational Fluid Dynamics (CFD) simulations on small hydrogen releases from hydrogen fuel cell inside a naturally ventilated facility and focused on the safety assessment in terms of ventilation efficiency. The initial leakage diameter was chosen based on the Italian technical guidelines for the enforcement of the ATEX European directive.

In the paper of Giannissi et al. (2015) a CFD benchmark was performed to study the release and dispersion of hydrogen in a naturally ventilated enclosure with one vent. The benchmark involved comparing CFD model predictions with measurements from an experiment carried out by the Health and Safety Laboratory (HSL) within the framework of the H2FC project. For the purpose of experiments hydrogen was released with sonic velocities vertically upwards through a 0.55 mm diameter nozzle located 0.5 m above the center of the floor of the enclosure. In the paper of Lee et al. (2022) a CFD model of natural and forced ventilation is presented as an emergency response to hydrogen leakages in pressure regulator equipment housing. The CFD model is developed and investigated using three different vent configurations: up, cross, and up-down. The simulation results indicate that the up-down configuration achieves the lowest internal hydrogen concentration out of the three. In addition, the relationship between the total vent size and internal hydrogen concentration is determined with the conclusion that a vent size of 12% of the floor area has the lowest hydrogen concentration. Hou et al. (2023) carried out numerical analysis of the effect of obstacles on hydrogen dispersion in enclosed spaces of a hydrogen fuel cell bus. Lee et al. (2017) conducted numerical analysis of hydrogen ventilation in a confined facility with various opening sizes, positions and leak quantities. They concluded that although numerical methods and commercial CFD software have been used widely, extensive validation is necessary in order for various cases to be performed reliably.

Ehrhart et al. (2021) analysed hydrogen release in a car repair garage. They concluded from CFD modelling results that with the type of ventilation that can be produced from a typical box fan, which would generate local ventilation velocities higher than typical ventilation, the amount of flammable mass is dramatically reduced to the point where it exists only directly near the leaking valve. Based on these results, authors suggested that use of direct ventilation might provide a suitable way to increase safety without structural changes to the garage or ventilation system.

Wang et al. (2023) established a CFD model of hydrogen leakage and diffusion of hydrogen production container with dimensions of 5×3.2×2.6 m. The sensitivity of critical ventilation flow parameters was analysed in this paper. It was found that in order to reduce the flammable volume by 85%, the installed ventilation can only cover the leakage flow of 1.0 Nm^3/min. Under the critical ventilation flow, the minor injury radius can be reduced from 4.8 m to 2.78 m.

In summary, numerical-based studies on hydrogen safety issues in automotive applications are numerous. These methods are already applied for hazard assessments and solutions for hydrogen leakage in scenarios such as fuel cells, cars, and garages. However, only few papers deal with analytical assessment of explosive atmospheres formed by hydrogen leakage in industrial applications such as electric power industry or chemical industry. Large enclosures are specific to these industries, where the application of numerical methods is time consuming and with high computing cost. Conducting experiments to validate the results of numerical models is also challenging in such environment.

As an alternative to numerical simulations in this paper influence of ventilation system availability and effectiveness is evaluated by applying standardized analytical methods for classification of areas of explosive atmospheres with the aim to obtain high dilution for non-hazardous zone or to reduce Zone 2 area within hydrogen storage room and transportation pipeline corridors.

Nomenclature

C	air change frequency in the room, 1/s
C_d	discharge coefficient, -
c_p	ideal gas heat capacity at constant pressure, J/(kg·K)
f	diluting effect factor, -
k	safety factor due to uncertainty of *LFL*, -
LFL	lower flammable limit, vol/vol
M	molecular weight, kg/kmol
p	pressure inside the container, Pa
p_a	atmospheric pressure, Pa
p_c	critical pressure, Pa
Q_g	volumetric flow rate of flammable gas from the source, m^3/s
Q_2	volumetric flow rate of air/gas mixture leaving the room, m_3/s
R	universal gas constant, J/(kg·K)
S	cross section of the opening (hole), through which the gas is released, m^2
T	absolute temperature of gas, K
T_a	absolute ambient temperature, K
V_0	volume under consideration (room or building), m^3
W_g	mass release rate of gas, kg/s
X_b	background concentration, vol/vol
X_{crit}	critical background concentration, vol/vol
Z	compressibility factor, -
γ	polytropic index of adiabatic expansion or ratio of specific heats, -
ρ_g	density of the gas or vapour, kg/m^3

2. Methodology

2.1. Gas release rate

Grade of hydrogen release and classification of explosive gas atmospheres is done in accordance with international standard EN IEC 60079-10-1:2022. Zone 2 is defined an area in which an explosive gas atmosphere is not likely to occur in normal operation but, if it does occur, it will exist for a short period only. The most common type of storage is high-pressure compressed hydrogen, with pressures of 50 to 100 bar, Tang et al. (2023).

The velocity of released gas is choked (sonic) if the pressure inside the gas container is higher than the critical pressure p_c.

Critical pressure is determined by the following equation:

$$p_c = p_a \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{(\gamma-1)}} \tag{1}$$

Critical pressures are generally low compared with the majority of operating pressures found in common industrial processes: terminal gas supply lines to fired equipment like e.g., heaters, furnaces, reactors, incinerators, vaporizers, steam generators and boilers.

Choked gas velocity is equal to the speed of sound (maximum theoretical discharge velocity). The release rate of gas from a container, if the gas velocity is choked, can be estimated by means of the following approximations:

$$W_g = C_d\, S\, p \sqrt{\gamma \frac{M}{Z\,R\,T} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \tag{2}$$

The volumetric flow rate of gas in (m^3/s) is equal to:

$$Q_g = \frac{W_g}{\rho_g} \tag{3}$$

Where

$$\rho_g = \frac{p_a M}{R\, T_a} \tag{4}$$

Grade of release is estimated as secondary leakage due to a seal rupture. Several leakage cross section areas are taken into consideration from secondary grade of releases: from S=0.025 mm^2 at flanges with compressed fiber and spiral wound gasket, S= 0.25 mm^2 at ring type joint connections up to S= 1 mm^2 at small bore connections.

Hydrogen storage pressures (p) were varied from typical spherical tank at 50 bar to vertical tube storage at 100 bar. Dimensionless discharge coefficient that accounts for the turbulence and viscosity is typically from C_d= 0.50 ÷ 0.75.

A characteristic of release in (m^3/s) is calculated as:

$$\frac{W_g}{\rho_g\, k\, LFL} \tag{5}$$

Safety factor (k) was varied from 0.5 to 1, due to uncertainty related to lower flammable limit (LFL) because of possibility of existence of hydrogen background concentrations which corresponds with the mean concentration of flammable substance within the volume under consideration outside of the release plume or jet.

2.2. Ventilation strategy

Gas or vapour released into the atmosphere may dilute through turbulent mixing with air, and to a lesser extent by diffusion driven by concentration gradients. Ventilation and air movement have two basic functions, to increase the rate of dilution and promote dispersion to limit the extent of a zone and to avoid the persistence of an explosive atmosphere that may influence the type of a zone. The presence of Zone 2 implies a greater risk of explosion and the obligation to install equipment that has ATEX certificates.

The effectiveness of the ventilation in controlling dispersion and persistence of the explosive atmosphere will depend upon the degree of dilution, the availability of ventilation and the design of the system. The most important factor is the effectiveness of ventilation, in other words the quantity of air relative to the type, release location and release rate of the flammable substance. The higher the amount of ventilation in respect of the possible release rates, the smaller will be the extent of the zones (hazardous areas) and shorter the persistence time of explosive atmosphere. With a sufficiently high effectiveness of ventilation for a given release rate, the extent of the hazardous zone may be so reduced to be of negligible extent (NE) and be considered a non-hazardous area. In case of secondary grade of release according to standard EN IEC 60079-10-1:2022, non-hazardous areas can be achieved in conditions of high dilution and with good or flair ventilation availability. Good ventilation is present virtually continuously while fair ventilation is expected to be present during normal operation. Discontinuities are permitted provided they occur infrequently and for short periods. Mechanical ventilation that serves the areas exposed to explosion conditions usually has a good availability because it incorporates technical means to provide for high degree of reliability.

In the reference standard three different types of ventilation strategy are considered: supply only ventilation, supply and extraction ventilation, and local extraction ventilation.

As with the case for supply only there is a possibility that the ventilation arrangement will create recirculating air movement and result in re-entrainment of the diluted gas into a jet release thereby increasing the background gas concentration. With careful consideration of the ventilation arrangements and positioning of the extraction points it is possible to minimize any re-circulatory air patterns. In this case a degree of dilution of medium or even high may be achieved.

2.3. Criteria for dilution

The criteria for dilution are based upon the two values that are characteristic for any release:

- the relative release rate calculated by equation (5);
- the ventilation velocity (the value that symbolizes the atmospheric instability, i.e. air flow induced by ventilation or wind speed outdoors).

The degree of dilution is obtained by finding the intersection of respective values displayed on horizontal and vertical axis in nomogram given in standard. A low degree of dilution will not generally occur in open air situations. For indoor applications the background concentration of hydrogen should also be assessed. The higher the ratio of release rate against the ventilation rate the higher will be the background concentration X_b and the lower will be the degree of dilution. The volumetric background concentration may be calculated as:

$$X_b = \frac{f \cdot Q_g}{Q_2} \quad (6)$$

and the air change frequency and ventilation flux are related by:

$$Q_2 = C \cdot V_0 \quad (7)$$

In assessing background concentration the release rate, ventilation rate and efficiency factor must be carefully defined to take into account all relevant factors considering an appropriate safety margin. The ventilation efficiency factor should recognize if there is a possibility of recirculating or impeded air flow in a space which may reduce the efficiency compared to a good air flow pattern. A zero background concentration should be considered only outdoors or in regions with local extraction ventilation which controls the movement of flammable substance near the source of release. A negligible background concentration, described as $X_b << X_{crit}$, may be considered in highly ventilated rooms or enclosures. X_{crit} is an arbitrary value below LFL, e.g., the value at which a gas detector is set to alarm, usually 10÷25% of LFL. A low background concentration does not mean that the whole room is a non-hazardous area. The larger part of the room may be considered non-hazardous but the area near the source of the release is still a hazardous area until the release is sufficiently dispersed.

The factor f in equation (6) is a measure of the degree to which the air in the enclosure outside of the release zone is well mixed and can be considered as follows: f =1; the background concentration is essentially uniform and the outlet is distant from the release itself, so that the concentration at the outlet reflects the mean background concentration. Factor f is usually between 1.5 for mildly inefficient mixing and 5 for very inefficient mixing.

3. Results and discussion

Calculations of hydrogen release characteristics have been done using equations (1) to (5) with assumed conditions described in chapter 2. The results are summarized in Table 1.

Table 1. Results of hydrogen release characteristics under different release conditions

Parameter/Scenario	#1	#2	#3	#4	#5	#6
p, Pa		$5 \cdot 10^6$			$10 \cdot 10^6$	
p_a, Pa			$0.1 \cdot 10^6$			
T_a, K			293			
R, J/(kg°C)			8,314			
M, kg/kmol			2.016			
c_p, J/(kgK)			14,310			
γ, -			1.405			
p_c, Pa			$0.192 \cdot 10^6$			
C_d, -	0.5	0.75	0.75	0.5	0.75	0.75
S, mm^2	0.025	0.25	1	0.025	0.25	1
Z, -			1			
W_g, kg/s	$3.9 \cdot 10^{-5}$	$58.8 \cdot 10^{-5}$	$233.9 \cdot 10^{-5}$	$7.8 \cdot 10^{-5}$	$116.9 \cdot 10^{-5}$	$467.7 \cdot 10^{-5}$
ρ_g, kg/m^3			0.084			
k, -	1	0.8	0.5	1	0.8	0.5
LFL, -			0.04			
$W_g/(\rho_g \cdot k \cdot LFL)$, m^3/s	0.012	0.218	1.395	0.023	0.436	2.789

In all cases $p>p_c$ thus hydrogen release is sonic. Based on calculated hydrogen release characteristics criteria of dilution is analysed for less favourable conditions (pressure of 100 bar, scenarios from #4 to #6) using nomogram shown in Fig. 1. The results have shown that in the case of gas discharge from an opening with a diameter of S=1 mm^2 (scenario #6), it is not possible to achieve high dilution scenario and avoid the Zone 2 area. The same conclusion can be drawn for gas release at 50 bar and opening diameter of S=1 mm^2 (scenario #3). In the case for gas release at 100 bar with opening diameter of S=0.25 mm^2, C_d=0.75 and k=0.8 the air velocity due to the operation of the ventilation system should be at least 6 m/s to achieve high dilution (scenario #5), which can be achieved by the proper selection of the ventilation system in closed spaces. In all other cases considered in the paper (scenarios #1, #2 and #4), the required ventilation air speeds are lower, so conventional ventilation systems (such as mechanical supply and extraction ventilation or local extraction ventilation) can be applied in order to prevent hydrogen explosive atmospheres.

Another nomogram (Fig. 2) from the standard is used to access hazardous distances from the release source for high velocity jet release, typical for hydrogen release at high pressure. The curves are based on a zero background concentration and are not applicable for indoor low dilution situations. Where a zone of negligible extent (NE) is suggested then the use of this nomogram is not applicable. For this reason hazardous distances are determined for scenarios #3 and #6, which equal to 2.5 and 3.7 m, respectively.

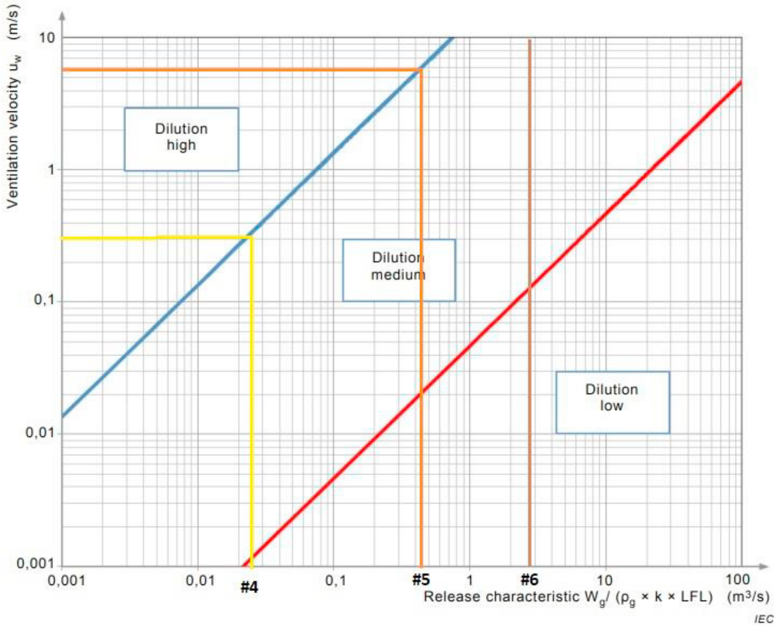

Fig. 1. Criteria of dilution for hydrogen release at 100 bar

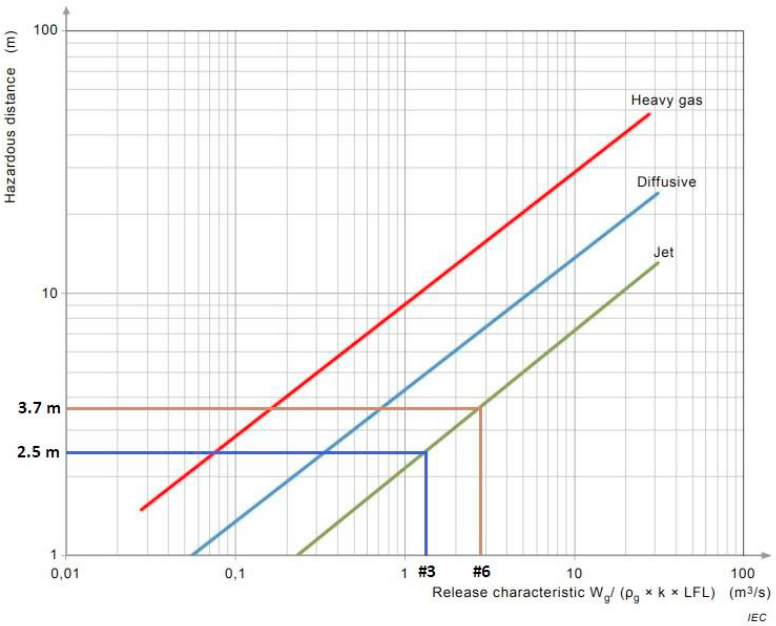

Fig. 2. Hazardous distances for hydrogen release at 50 and 100 bar, S=1 mm^2, C_d=0.75 and k=0.5

Background concentration release rates are calculated from equation (6) and (7) for the scenario #1 assuming volume of industrial hall of V_0=5,000 m^3. Different ventilation air change rates per hour (ACH) are considered, such as standard industrial 5 ACH up to 30 ACH typical for explosive atmospheres ventilation. Also, the factor f which accounts for background concentration uniformity, assumed to be 1.5, 3 and 5 while X_{crit} is adopted to be 0.25% of·LFL value. The results of background concentration calculations are presented in Table 2.

Table 2. Results of hydrogen background concentration calculations

Parameter/Scenario	#1.1	#1.2	#1.3	#1.4	#1.5	#1.6
f, -	1.5	3	5	1.5	3	5
Q_g, m^3/s	0.012					
C, 1/hr	5	5	5	30	30	30
Q_2, m^3/s	13.89	13.89	13.89	41.67	41.67	41.67
X_b, vol./vol.	0.0013	0.0025	0.0042	0,0004	0,0008	0,0014
X_{crit}, vol./vol.	0.01					

From the results it can be concluded that negligible background concentration ($X_b << X_{crit}$) can be achieved in case of 30 ACH (scenario #1.4 to #1.6) and even for the case of 5 ACH and f=1.5 (scenario #1.1).

4. Conclusions

The results of the analytical study have shown that in the case of hydrogen discharge from an opening with a diameter of 1 mm^2, it is not possible to achieve high dilution scenario and avoid the Zone 2 area. Hazardous distances were estimated at 2.5 and 3.7 m from the source of release at pressure of 50 and 100 bar, respectively. In the case of gas release at 100 bar with opening diameter of 0.25 mm^2, air velocity induced by mechanical ventilation should be at least 6 m/s to achieve high dilution and consequently zone of negligible extent. This can be achieved by the proper selection of the ventilation system in closed spaces. In all other cases considered in the paper the required ventilation air speeds are lower, so conventional ventilation systems (such as mechanical supply and extraction ventilation or local extraction ventilation) can be applied in order to prevent hydrogen explosive atmospheres. The results also shown that negligible background concentration of hydrogen in industrial halls can be achieved with ventilation system that can provide 30 ACH.

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