EXPLOSION RISK ASSESSMENTS FOR FACILITIES WITH COMPRESSED FLAMMABLE GASES

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Research article

Abstract: In the first part of the article we discuss the possibilities and analytical tools that can deal with the classification of space into zones with danger of explosion for devices with the presence of compressed flammable gases. Then we continue with specifications of possibilities for practical utilization linked to variables such as ventilation degree, hypothetical volume etc., including the examples. At the end we also give a brief overview of software for modelling gas leak, including examples of an outcome.

Keywords: Explosion, fire, pressure, flammable gas, leak.

Introduction

The occurence of flammable gases can be seen in wide range of industrail branches. Mostly they are applications where the flammable gases are transported (pipe distribution network) or stored (gas storages and cylinders) under pressure in both, liquid and gaseous states. Tab. 1 shows the overview of technical-safety parameters of the most frequent industrial flammable gases (Gestis-Dust-Ex, 2014). We cover also compressed natural gas (CNG) and liquified petroleum gas (LPG), which are becoming more and more widespread these days, especially as the alternative fuels for classical engines.

Note:

Values of the technical-safety parameters of gases specified in material safety data sheets can vary according to the purity of the gas and according to the reproducibility of the used testing method.

Classification of spaces with risk of explosion is provided in directive 1999/92/ES as follows (Directive, 1999).

Zone 0: Place where the explosive atmosphere, made by mixture of air and flammable substances in the form of gas, vapour or mist, is present permanently or for a long period or frequently.

Zone 1: Place where occasional occurrence of explosive atmosphere, made by mixture of air and flammable substances in the form of gas, vapour or mist, is likely.

Zone 2: Place where occurrence of explosive atmosphere, made by mixture of air and flammable substances in the form of gas, vapour or mist is not

Tab. 1 Overview of selected technical-safety parametres of most frequent flammable gases (Gestis-Dust-Ex, 2014)

	Flash point [°C]	Ignition temperature [°C]	Lower explosion limit [vol. %]	Upper explosion limit [vol. %]	Temperature class
Hydrogen		560	4	77	T1
Methane		595	4,4	17	T1
Propane	-104	450	1,7	10,8	T2
Buthane	-60	365	1,4	9,4	T2
Carbon Monoxide	-191,6	605	11,3	75,6	T1
CNG		537	4,4	15	
LPG		430	1,5	9,5	

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likely, and if it arises, it is present exceptionally or for a short period only.

Space assessment is a method of analysis and environment classification where the explosive atmosphere can arise; it is carried out to provide appropriate choice and instalment of the devices, so that they can be used safely in the particular environment. Classification into zones is dependent on many factors, as type of leak source, velocity of leak, ventilation parameters, physical-chemical properties of the hazardous substance etc.

Appropriate tools for place classification are listed in appendixes A and B (ČSN EN 60079-10-1, 2009), including practical examples.

Assessment of ventilation degree and its effect on spaces with explosion risk

According to (ČSN EN 60079-10-1, 2009) individual leak sources can be classified according to degree of leak:

Permanent leak degree - leak which is permanent or we expect its occurrence frequently or for long periods, e.g.:

- surface of flammable liquid in a tank with hardtop and permanent ventilation into the atmosphere,
- surface of flammable liquid which is opened into the atmosphere permanently or for a long period.

Permanent leak degree usually results in assessment of the space as Zone 0.

Primary leak degree - leak whose occurrence can be expected periodically or occasionally during normal operation, e.g.:

- safety valves, relief openings and other openings which suppose leak of flammable substances into the atmosphere under normal operation etc.

Primary leak degree usually results in assessment of the space as Zone 1.

Secondary leak degree - leak whose occurrence is not expected under normal operation, and if it occurs, it is likely only rarely and for short periods, e.g.:

- flanges, connections and fittings for pipelines where we do not expect leak of flammable substance under ordinary operation etc.

Secondary leak degree usually results in assessment of the space as Zone 2.

Size of flammable gas cloud is influenced by ventilation. Standard (ČSN EN 60079-10-1, 2009) describes method of ventilation degree assessment, needed for influencing the extent of explosive atmosphere. The standard warns that the method has its limitations, thus it gives only approximate results.

To assess the ventilation degree, it is necessary to know maximum leak velocity of gases from the leak source, either based on verified experience, justified by calculation or assessment, or accessible data from the manufacturer (ALOHA User´s Manual, 2007).

Estimation of hypothetical volume V_z

Hypothetical volume V_z represents the volume, in which the mean concentration of flammable gases or vapours equals the factor of 0.25 LEL (lower explosive limit) or factor of 0.5 LEL, depending on the value of safety coefficient *k*. It means that in the limit areas of the estimated hypothetical volume, the concentration of gases shall be significantly lower than LEL and the volume, in which the concentration of gases is over LEL, shall be less than V_z.

Calculation of V_z is determined to support the assessment of ventilation degree. The standard in article B 5.2.1 states that the hypothetical volume has no direct relation to the dimension of the hazardous space.

Relation between hypothetical volume V_z and dimensions of the hazardous space

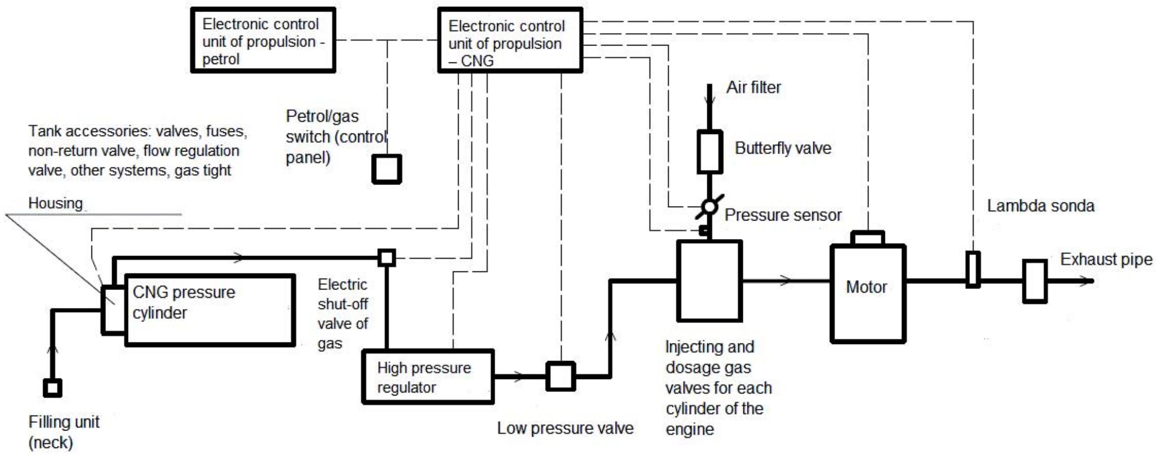
Hypothetical volume gives the idea of volume of enclosure with explosive atmosphere ambient to the leak source, the enclosure will not usually be equal to the volume of hazardous space. The shape of hypothetical volume is not defined and is effected by ventilation conditions. Further on it is necessary to determine the location of the hypothetical volume in relation to the leak source, which shall depend on direction of ventilation and spreading of the hypothetical volume in the direction of wind flow. Thus the volume of hazardous space from the leak source shall usually be several times higher than the hypothetical volume.

Relation between hypothetical volume V_z and ventilation degree

According to calculated hypothetical volume it is possible to determine so called ventilation degree. We differentiate three ventilation degrees:

Good ventilation degree

Ventilation can be considered as high rate one if the hypothetical volume V_z is lower than 0.1 m^3 or smaller than 1 % V_o - complex volume of the space where the leak source is located (always the lower value is taken into account). In reality we can reach the high rate ventilation only with the systems of local forced ventilation in the surrounding of leak



Scheme 1 Simplified block diagram of CNG propulsion

Tab. 2 Table of classification into zones (ČSN EN 60079-10-1, 2009)

Leak degree	**Ventilation**						
	Degree						
	good			**medium**			**poor**
	reliability						
	excellent	**satisfactory**	**low**	**excellent**	**satisfactory**	**low**	**excellent, satisfactory, low**
Permanent	(zone 0 NE) No hazard[a]	(zone 0 NE) zone 2[a]	(zone 0 NE) zone 1[a]	zone 0	zone 0 + zone 2	zone 0 + zone 1	zone 0
Primary	(zone 1 NE) No hazard[a]	(zone 1 NE) zone 2[a]	(zone 1 NE) zone 2[a]	zone 1	zone 1 + zone 2	zone 1 + zone 2	zone 1 or zone 0[b]
Secondary	(zone 2 NE) No hazard[a]	(zone 2 NE) No hazard[a]	zone 2	zone 2	zone 2	zone 2	zone 1 even zone 0[b]

source for small enclosed spaces or for very low leak velocity.

Poor ventilation degree

Ventilation can be considered as low rate if the value of hypothetical volume V_z is higher than the volume of space where the leak source is located.

Medium ventilation degree

If ventilation does not meet the requirements for good or poor ventilation degree, we consider it as medium ventilation degree.

Ventilation effecting the type of zone

In the table below we can see the effect of leak degree and ventilation on type of zone with risk of explosion, as presented in the (ČSN EN 60079-10-1, 2009).

Note:

a Zones 0 NE, 1 NE, 2 NE - they are theoretical zones, in normal conditions they are of negligible range.

b Zone 0 shall be determined if the ventilation is poor and leaks of such a kind that the explosive gaseous atmosphere is present permanently (i.e. it is close to the conditions without any ventilation at all).

+ Means „which surrounds“.

Note:

If possible, permanent or primary leak sources should not be placed in spaces with poor ventilation degree. In such a situation the leak source shall be re-located or ventilation shall be improved or the leak degree shall be reduced.

Case study - CNG leak

Individual concepts can be compared, e.g. on risk analysis of explosive concentration occurrence, made by natural gas at the malfunction/leak from fuelling system of an automobile with such propulsion. As the base for comparison we have chosen the scenario used by Dipl. Ing. Dr. Bernhard SCHNEIDER (Schneider, 2007) as the "worst-case" scenario with natural gas leak from fuelling system of an automobile with CNG (compressed natural gas) propulsion.

Specification of the worst-case scenario 330 [µm] crack in the pressure cylinder of natural gas with volume of 100 [l] and charging pressure of 200 [bar]

One of the conclusions states that during first ten minutes 1.086 kg of gas leaks into the space through the crack (in the worst-case scenario the study calculates that during 682 minutes 14.336 kg of gas leaks, during last 2 hours it will be only circa 0.14 kg). From the presented information we can conclude that at in case of this leak scenario, in garages with area of 250 m^2, with air change of 0.5, the concentration of 2.4 % volume of natural gas in the air will be reached.

Example of assessment methodology for spaces pursuant to (ČSN EN 60079-10-1, 2009)

The calculation has been carried out for a pressure cylinder of volume V = 100 l, charging pressure p = 20 MPa, size of crack d = 330 µm, temperature inside the tank T = 20 °C, for methane. For the purposes of the assessment we considered the garage with inner volume V_0 = 2 000 m^3.

Substance		methane
Leak degree		secondary
Lower explosion limit (LEL)	(4.4 vol. %)	0.029 kg.m^{-3}
Molecule weight		16.04 kg.kmol^{-1}
Polytropic index of adiabatic expansion		1,302
Safety coefficient (k)		0.5
Coefficient of air dilution (f)		1
Ambient temperature (T)		20 °C (293,15 K)
Temperature coefficient (T/293)		1
Initial concentration of flammable substance (X_0)		100 %
Volume of inner garage space (V_0)		2000 m^3
Atmospheric pressure (p_0)		0,101 MPa
Pressure of the gas inside of the tank (p_c)		20 MPa
Number of air changes in the room (c)	0.5.hod^{-1}	0,000138 s^{-1}

At first it is necessary to estimate the critical pressure and compare it with a pressure inside of the tank (p_c). If p_c ishigher than critical pressure, than velocity of gas leak will be restricted to sound velocity of that gas and can be estimated through the equation which is mentioned in the standard. If p_c is lower than critical pressure, than velocity of gas leak will be subsonic and can be estimated through another equation mentioned in the standard.

Critical pressure

$$p_c = p_o\left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} = 0{,}101\cdot\left(\frac{1{,}302+1}{2}\right)^{1{,}302/(1{,}302-1)} = 0{,}19\ \text{MPa}$$

where γ is polytropic index of adiabatic expansion.

Velocity of gas leak will be restricted to sound speed because pressure inside the tank is higher than critical pressure.

Velocity of gas leak from the tank or respectively the circuit can be estimated through the below mentioned equation for restricted velocity of the gas leak:

$$\frac{dG}{dt} = S\cdot p\cdot\sqrt{\gamma\frac{M}{R\cdot T}\cdot\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)}}$$

where p is pressure inside the tank [Pa]; S cross-section of opening the gas leaks through [m^2]; M molar weight of the gas [kg/kmol]; T absolute temperature inside the tank [K]; γ polytropic index of adiabatic expansion [-]; R universal gas constant [8 314 J.kmol^{-1}.K^{-1}].

After completing the equation we obtain $\frac{dG}{dt}$ = 2.93.10^{-3} kg.s^{-1} for velocity of gas leak from the pipeline.

Minimum volume velocity of fresh air flow:

$$(dV/dt)_{\min} = \frac{(dG/dt)_{\max}}{k\cdot \text{LEL}}\cdot\frac{T}{293} = \frac{2{,}93.10^{-3}}{0{,}5\cdot 0{,}029}\cdot\frac{293}{293} = 0{,}202\ \text{m}^3.\text{s}^{-1}$$

Assessment of hypothetical volume:

$$V_z = \frac{f \cdot (dV/dt)_{\min}}{c} = \frac{1 \cdot 0,202}{0,000138} = 1464,3 \text{ m}^3$$

Materials and methods

Hypothetical volume is smaller than the inner garage volume. Ventilation degree is considered to be medium, however not of negligible range (V_z > 0.1 m^3). Reliability of ventilation can be considered as medium. Based on the calculations and assessment of ventilation according to table B. 1 (ČSN EN 60079-10-1, 2009) the space ambient to the garage must have been classified as Zone 2.

Modelling of potential CNG leak scenarios

None of the accessible used modelling programmes is primarily determined for solution of these functions (minor leak, high pressure, enclosed space etc.). Therefore we tried to come as close as possible to the conditions of the worst-case scenario. For the purposes of modelling, two representative scenarios of potential leak had been chosen:

1. Safety valve failure and leak of full volume of the CNG cylinder

2. Minor leak through CNG leakage

Leak of CNG can be caused by leakage of pressure cylinder, valves or pipeline. The leakage can be caused by corrosion, fatigue of material constructional defect, mechanic damage or bad maintenance. The most probable is the leak of gas and its concentrating in the vehicle or the garage (so called gas nest) and consecutive fire (Flash Fire) or explosion (VCE - Vapour Cloud Explosion).

For modelling we used accessible programmes - ALOHA (developed by American association for environment protection US EPA (ALOHA User´s Manual, 2007), (Program EFFECTSGIS 5.5, 2004) by the Dutch company TNO and (TerEx) by the Czech company T-Soft. The programmes had been used for modelling of risk zones of CNG leak, even though they are determined for modelling in open spaces. Thus the results must be understood as approximate conditions for underground garages.

From the data we can conclude following facts. The major risk at CNG leak is the Flash Fire. Vapour cloud explosion (VCE) can occur only exceptionally in enclosed (so called overfilled) zones. For selected leak sources we have determined relevant representative scenarios of possible CNG leak under following conditions:

- out of meteorological conditions we have chosen two basic: D stability class, wind speed of 5 m/s, air temperature of 20 °C - representing the conditions in the underground garage with sufficient forced ventilation; F class stability, wind speed of 1.7 m/s, air temperature of 10 °C - representing insufficient ventilation of underground garages;
- with respect to the possibility of installing detectors in the underground garages, risk zones were modelled for 10 % and 60 % of lower explosive limit (LEL) and above 100 % concentration of lower flammability limit for determination of zone with risk of Flash Fire or VCE;
- as it is impossible to know the CNG composition in advance, we approximate important CNG properties by its main component methane for the purposes of modelling.

Following table illustrates overall results of modelling for two representative scenarios by modelling tools (ALOHA User´s Manual, 2007), (Program EFFECTSGIS 5.5, 2004) and (TerEx). Each of the scenarios had been modelled variably for different weather conditions relevant to Pasquil´s classes of D and F, which were approximately similar to different types of ventilation in underground garages.

Tab. 3 Survey of modelling results of hazardous CNG spaces (ALOHA User´s Manual, 2007; Program EFFECTSGIS 5.5, 2004; TerEx)

Scenario	**Situation (stability class)**	**Assessed parameter (zone of risk) [m]**						
		ALOHA			**EFFECTS**			**TerEx**
		(100 % LEL) 44 000 ppm	**(60 % LEL) 26 400 ppm**	**(10 % LEL) 4 400 ppm**	**(100 % LEL) 29351 mg/m^3**	**(60 % LEL) 17610 mg/m^3**	**(10 % LEL) 2935 mg/m^3**	**100 % LEL**
1	D	< 10	< 10	18	-	-	-	32
	F	19	24	60	-	23	62	73
2	D	< 10	< 10	< 10	-	-	-	21
	F	< 10	< 10	14	-	-	-	85

Safety Engineering Series DOI 10.1515/tvsbses-2015-0008

Note:

The dash means that the programme did not determine particular concentration.

Results

Result comparison from the single programmes is difficult. With respect to different principles of the programmes and possibilities of entering the initial data, it is not possible to compare the results in a simple way. Mainly (TerEx) programme is set for quick modelling in cases of rescue unit interventions and does not enable detailed entering of initial data, as it works with other two programmes. Still we can make following conclusions based on the results:

- (ALOHA User´s Manual, 2007) programme did not assess exact distance of lower explosion limit occurrence in most of the cases, when in case of occurrence of this concentration ambient to the leak source rounds the results to less than metres and does not provide graphic outcome;
- (Program EFFECTSGIS 5.5, 2004) programme did not determine required concentrations, i.e. concentration of lower explosion limit should not occur;
- (TerEx) programme determined relatively great distances where it is necessary to evacuate all people before flash of the flame.

Discussion

For comparison of outcomes from the concepts we have intentionally chosen relatively complicated, but entirely current case. It is obvious that the key role in assessment and classification of hazardous spaces belongs to the air change inside the space, further on geometrical shape, substance properties etc.

From the scenarios we have modelled there follows that in case of well ventilated garages, the dangerous concentration can occur only in vicinity of the place of CNG leak from the vehicle. In cases of poorly ventilated garages we can assume the likeliness of fire or cloud explosion on the order of the first tenths of metres.

The final results could be verified by CFD (Computational Fluid Dynamics) models. By their application we could reach more exact results on order of magnitude, including the options of influencing the dissipation of obstacle presence. Creating such models is significantly more difficult, with respect to time needed to prepare the model, and also the time needed for the calculation itself.

For purposes of the comparison of the garage space we have used the methodology of ventilation degree classification according to (ČSN EN 60079-10-1, 2009) which helps and is perceived only as a possible base and method for assessment of these spaces. From the presented example of assessment classification for spaces, according to the above mentioned standard, it cannot be concluded that the garage space with parking possibilities for CNG vehicles necessarily must be classified as Zone 2, provided that suitable conditions and provisions are met.

For purposes of calculation of the gas leak velocity, which is required to ventilation degree classification according to ČSN EN 60079-10-1, is necessary to know the surface area of the hole (crack) through the gas is escaping. However size of that hole (crack) is not specified in any legal act in Czech Republic. Without estimation of the hole size is not possible to do qualified assessment of the explosive atmosphere occurrence. Therefore for demands of this assessment was adopted the hole size which is specified in study of the Dipl. Ing. Dr. Bernhard Schneider from 2007. In model scenario of that study was used the leak in CNG fuel system of the car with diameter 330 µm.

Conclusion

The aim of the article is to survey options and processes which can be used for risk analysis solutions of explosions at devices with compressed flammable gases. Due to diverse requirements on initial data, it is apparent that the final results are very difficult to be compared and evaluated. From the analysis we carried out, it can be concluded that one of the most important steps in the solution is the choice of an appropriate assessment tool and sufficient experience with its application.

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Safety Engineering Series DOI 10.1515/tvsbses-2015-0008

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