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A Methodological Approach for the Characterization of Hazardous Zones due to Potentially Explosive Atmospheres: a Case Study

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The biogas role is becoming crucial in the panorama of sustainable development. In fact, Countries of the European Union have agreed on a new 2030 Framework for climate and energy, which includes targets aimed at achieving a more competitive, secure and sustainable energy system. A specific target has established that at least a 27% share of renewable energy consumption must be achieved. Biogas sector is quickly developed in Italy, which is the second biogas producer in Europe, after Germany, and by the end of 2017 about 1,900 plants were operating. One of the main hazards, associated with the biogas production, is the formation of potentially explosive atmospheres (methane is present in biogas composition), deriving from accidental biofuel releases. Indeed, in the industrial plants there are several potential sources, such as valves, flanges, compressors, etc.. The paper illustrates a case study, referred to a biogas production plant. In particular, the paper describes a methodological approach aimed at classifying the places (zone 0 or zone 1 or zone 2 or non-hazardous zone), where potentially explosive atmospheres could occur, and characterizing explosive atmosphere geometry in terms of extent and volume. This topic plays a very important role in order to ensure a safer operation of the plants, because classification of hazardous areas allows to choose equipment and protective systems (according to Atex Directive 2014/34/EU) intended for use in potentially explosive atmospheres. The classification has been carried out in accordance with Atex Directive 99/92/EC, which states the minimum requirements for improving the safety and health protection of workers exposed to potentially explosive mixtures.

1. Introduction

Some european countries have a considerable number of biogas production plants and this number continues to grow (Deublein and Steinhauser, 2011). It is generally known that the accidents number increases with a higher number of units (Casson Moreno et al., 2015). Several accidents are due to the formation of potentially explosive atmospheres (Dupont and Accorsi, 2006), generated by accidental biogas releases. In fact, because of methane presence in its composition, biogas in combination with air can form explosive mixtures (Chrebet and Martinka, 2012). Indoor workplaces are the most hazardous areas (Harpude et al., 2014) with regard to formation of explosive atmospheres and therefore, in such zones, artificial ventilation system design plays a fundamental role in order to dilute the explosive mixture in shortest times. In a biogas production plant a typical dangerous zone is the container (indoor place), which includes the combined heat and power (CHP) unit. In the industrial plants, the hazardous zones are due to release from potential sources (valves, flanges, compressors, etc.). A plant component is considered as a potential source, when its failures are expected during the operation. On the contrary, it has to be remembered that catastrophic elements failures are not considered as potential sources, because they are beyond the concept of abnormality, reported in technical Standards. The classification of workplaces, where explosive atmospheres can form, is an obligation (European Parliament and Council, 1999), which is attributed to the employer by Directive 99/92/EC. In the paper, the examined biogas release source is the compressor, which adjusts the biofuel pressure in order to improve the engine performances. In particular, a compressor operating pressure variation (biogas emission

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pressure) has been considered for assessing its influence on biogas mass flow, ideal volume of explosive atmosphere (V_z) and hazardous distance (d_z). Such variation ranges between 0.8 p_{max} (241 kPa) and p_{max} (301.3 kPa).

2. Materials and Methods

Technical Standards EN IEC 60079-10-1 and IEC 31-35 have been used to classify the zone, where a potentially explosive mixture could form, and characterize it in terms of extent and volume. Areas classification depends on three parameters (IEC, 2012):

1) source release grade (continuous, primary or secondary);
2) ventilation degree (high, medium or low);
3) ventilation availability (good, fair or poor).

The first parameter is determined by the analysis of element operating conditions, whereas the others mainly depend on natural ventilation (outdoor places) or artificial ventilation systems in case of indoor places.

3. The case study: the biogas production plant

The plant is located near Rome and produces biogas from liquid manure (130 m^3/day) and maize silage (22 t/day). The examined release source is the compressor, which adjusts the biogas pressure in order to improve the performances of CHP unit. Biogas emission from compressor is due to its seal. Such machine is a water-cooled single stage rotary compressor and is installed in the container (Figure 1), which also includes the cogenerator. Container volume (V) is about 118 m^3.

Figure 1: Container

The compressor is equipped with a motor intended for control via frequency inverter. Maximum biofuel outlet pressure (p_{max}) is about 301.3 kPa. Before reaching the compressor, biogas is subjected to desulfurization (hydrogen sulfide concentration is decreased) and dehumidification (water concentration is decreased), which cools the gas flow until 10 °C. Container ventilation is ensured by a forced ventilation system and an emergency ventilation plant, which operates in case of failure of artificial ventilation system, which is able to guarantee a maximum air flow (Q_a) of about 30,000 m^3/h. The following biogas composition has been assumed: 60% CH_4 (v/v), 40% CO_2 (v/v).

3.1 Classification of hazardous zones (indoor places): the methodological approach

In order to classify the hazardous zone, generated by compressor emission, a methodological approach has to be applied to determine source release grade, ventilation availability and degree. Source release grade is determined by the analysis of element operating conditions. In this case, the compressor is considered as a source of secondary grade, because its emission is not expected to occur in the normal operation and if it should occur, it would be for a short time. Ventilation availability is determined by the analysis of operating conditions of forced ventilation system (Lauri et al., 2013). In this case, the maximum air flow and ventilation continuity, which is ensured by the emergency plant, allow to consider ventilation availability as fair. In Figure 2 the methodological approach is described. In particular, the procedure, which allows to determine the ventilation degree, is reported. The first step consists in locating the emission source and determining its release grade. Successively, the emission area has to be estimated. With reference to this topic, Technical Standard IEC 31-35 can be used to estimate the compressor emission area (A). The next phase consists in determining the biogas outflow (subsonic or sonic) by the calculation of critical pressure (p_{cr}):

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

Where:

- p_{cr} is the critical biogas pressure (Pa);
- p_a indicates the atmospheric pressure (Pa);
- γ (dimensionless parameter) is the polytropic index of adiabatic expansion.

The outflow is sonic, when p_r (biogas release pressure)>p_{cr}, otherwise it will be subsonic. The outflow determination is required to choose the equation, which allows to calculate the biogas mass flow (M_b):

$$M_b(kg/s) = A \cdot p_r \cdot C_d \cdot \sqrt{\gamma \cdot \frac{PM_b}{R \cdot T_1} \cdot \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}} \rightarrow \text{sonic outflow} \tag{2}$$

$$M_b(kg/s) = A \cdot p_r \cdot C_d \cdot \sqrt{\frac{\gamma}{\gamma - 1} \cdot \frac{2PM_b}{R \cdot T_1} \cdot \left[\left(\frac{p_a}{p_r} \right)^{\frac{2}{\gamma}} - \left(\frac{p_a}{p_r} \right)^{\frac{\gamma + 1}{\gamma}} \right]} \rightarrow \text{subsonic outflow} \tag{3}$$

Where:

- A (m^2) is the hole area (compressor emission);
- C_d indicates the discharge coefficient (dimensionless parameter);
- PM_b is the molecular weight of biogas (kg/kmol);
- T_1 represents the biogas release temperature (K).

In an indoor place, such as container, in order to determine the ventilation degree, X_m% (vol/vol), which indicates the average biogas concentration, has to be calculated. In order to determine this parameter, sources emission contemporaneity has to be considered, because hazardous biogas concentrations can be present both near the source and far from the release point (Pietrangeli and Lauri, 2018). In case of source (compressor) of secondary grade, X_m% is calculated by the following equation, reported in Technical Standard IEC 31-35:

$$X_m\% = \sum_{i=1}^{n} X_{r_{i(continuous)}} + \sum_{i=1}^{n} X_{te_{i(primary)}} + X_{te_{(secondary)}} \tag{4}$$

X_{r_i} is biogas concentration (expressed in volumetric percentage) referred to continuous grade sources and can be determined by the equation:

$$X_{r_i} = 100 \cdot \frac{M_{b_i}}{Q_a \cdot \rho_{b_i}} \tag{5}$$

Where:

- ρ_b is the biogas density (kg/m^3).

In case of sources of primary or secondary grade, $X_{te_{i(primary)}}$ and $X_{te_{i(secondary)}}$ (expressed in volumetric percentage) are calculated by the following equation:

$$X_{te_i} = 100 \cdot \frac{M_{b_i}}{Q_a \cdot \rho_{b_i}} \cdot \left(1 - e^{-C \cdot t}\right) \tag{6}$$

Where:

- C is the number of air changes (s^{-1}) and is calculated by the ratio between Q_a and container volume (V);
- t represents the release duration (s).

In the container there are not sources of continuous grade, but there are three sources of primary grade:

1) compressor safety valve (its mass flow is equal to $1.5 \cdot 10^{-4}$ kg/s);
2) CHP unit safety valve (its mass flow is equal to $1.54 \cdot 10^{-4}$ kg/s);
3) biogas engine shut-off valve vent (it happens at each shutdown of the engine); its mass flow is equal to $0.25 \cdot 10^{-3}$ kg/s.

The next step consists in comparing X_m% and (k LEL_V)/f:

- k (dimensionless parameter) is a safety factor, which depends on source emission grade;
- LEL_V (% vol/vol) is the lower explosive limit of biogas;
- f indicates the efficiency of ventilation in terms of its effectiveness in diluting the explosive atmosphere; f ranges from 1 (ideal situation) to 5 (impeded air flow).

If X_m% > (k LEL_V)/f, ventilation degree is low, otherwise it will be medium or high and its determination depends on persistence time (t_p) and ideal volume (V_z) of explosive mixture (Figure 3):

$$t_p(s) = -\frac{f}{C} \cdot \ln\left(\frac{k \cdot LEL_V}{X_0} \right) \tag{7}$$

$$V_z(m^3) = \frac{f \cdot M_b \cdot T_a}{C \cdot k \cdot LEL_m \cdot 293.15} \quad (8)$$

In equation 7, X_0 is the initial concentration of flammable substance (biogas) and, in case of gases, is equal to 50 %. In equation 8, T_a (K) and LEL_m (kg/m^3) respectively indicate the air temperature and mass based lower explosive limit. If persistence time of explosive atmosphere is short (it does not exceed 1-2 minutes) and V_z is lower than 0.1 m^3, the ventilation degree will be high, otherwise it will be medium (IEC, 2012). At this point, it is possible to classify the hazardous zone by Table 1 (IEC, 2016). The next step consists in determining the extent (geometrical characterization) of explosive atmosphere. In order to calculate the extent, IEC 31-35 introduces a parameter d_z, called hazardous distance. Such parameter depends on gas release pressure (p_r):

$$p_r < 500Pa \rightarrow d_z(m) = k_z \cdot \left(\frac{42{,}300 \cdot M_{gas} \cdot f}{PM_{gas} \cdot k_{dz} \cdot LEL_V \cdot v_a}\right)^{0.55} \quad (9)$$

$$p_r \geq 500Pa \rightarrow d_z(m) = k_z \cdot 50 \cdot \frac{PM_{gas}^{-0.65}}{k_{dz} \cdot LEL_V} \cdot \left(\frac{M_{gas}}{\varphi \cdot C_d}\right)^{0.5} \cdot \left[\gamma \cdot \left(\frac{2}{\gamma+1}\right)^{\beta}\right]^{-0.25} \cdot T_1^{0.25} \quad (10)$$

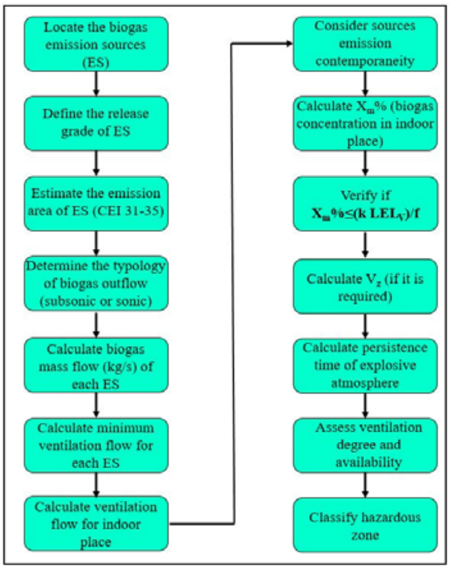

Figure 2: Classification of hazardous zones (indoor places)

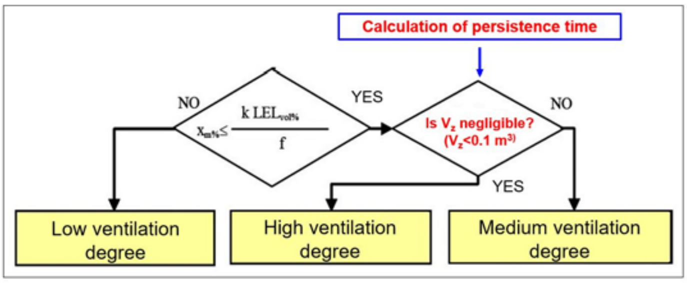

Figure 3: Ventilation degree assessment (indoor places)

Table 1: Classification of hazardous zones due to potentially explosive atmospheres

Release Grade	Ventilation Degree: High — Availability: Good	High — Fair	High — Poor	Medium — Good	Medium — Fair	Medium — Poor	Low — Good, fair or poor
continuous	(Zone 0 NE) Non hazardous zone[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) Non hazardous zone[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) Non hazardous zone[a]	(Zone 2 NE) Non hazardous zone[a]	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 or Zone 0[b]

Glossary
"+" means "surrounded by".
[a]Zone 0 NE, 1 NE and 2 NE indicate areas, which have negligible extents.
[b] Zone 0 can be generated in poor states of ventilation.

In equation 10 $\beta = \frac{\gamma+1}{\gamma-1}$. In the practical experience, d_z is increased of about 20% (Lauri, 2016) in order to estimate the real extent (a) of explosive atmosphere and increase the safety margin. In fact, the hazardous distance is the distance from the release source to where an explosive (biogas/air) mixture will be diluted by the air to a concentration (such concentration is equal to $k_{dz} \cdot LEL_V$, where k_{dz} is a dimensionless parameter, which is lower than 0.75) below the lower explosive limit. The volume of explosive mixture depends on p_r and can be represented by a cylinder or a cone (IEC, 2012). Cylindrical geometry can be used for every value of release pressure, whereas conic geometry can be only chosen in case of $p_r \geq 500$ Pa (IEC, 2012).

4. Results and discussion

In the case study, it has been assumed that all the sources are characterized by the same release time (t). Maximum release pressure (p_{max}) has been considered (Table 2) to classify the hazardous zone, caused by compressor emission. The parameters, used to classify the area, are reported in Table 2, whereas the results are shown in Table 3. As X_m% is lower than $k \cdot LEL_V/f$, V_z and t_p have been calculated to assess the ventilation degree (compressor release grade and ventilation availability have previously been determined). The ideal volume of explosive mixture is equal to 0.96 m^3 (V_z>0.1m^3) and persistence time is about 75 s. It follows that ventilation degree is medium (Figure 3). The values of source release grade (secondary), ventilation availability (fair) and degree (medium) determine a zone 2 (Table 1), generated by compressor emission. With reference to zone 0 and zone 1, zone 2 is the less hazardous area. In fact, zone 2 is an area, in which an explosive mixture is not expected during the normal operation and if it should form, its persistence time would be extremely short. On the contrary, zone 0 is the most hazardous area, because the explosive atmosphere is present for long periods.

Table 2: Parameters

Parameter	Value
k	0.5
f	2
LEL_V (v/v %)	7.3
PM_b (kg/kmol)	27.2
V (m^3)	118
T_1 (K)	283.15
p_{max}=p_r (kPa)	301.3
$c_{p(biogas)}$ (J/kg K)	1,442
$c_{v(biogas)}$(J/kg K)	1,080
γ	1.34
ρ_a (kg/m^3)	1.204
t (s)	600
C_d	0.8
A (m^2)	0.0000025
k_{dz}	0.5
k_1	82

Table 3: Results

Parameter	Value
p_{cr}(kPa)	187.831
biogas outflow	sonic
M_b (kg/s)	0.0014
C (s^{-1})	0.07
X_m%	0.43
k LEL_V/f (%)	1.825
t_p (s)	75
V_z (m^3)	0.96
ventilation degree	medium
Zone	2
φ	1 (sonic flow)
β	6.97
k_z	1.19
d_z (m)	0.4
a (m)	0.48
ρ_b (kg/m^3)	3.48

The extent of zone 2 (hazardous area) has been estimated by equation 10 (p_r>500 Pa) and its value is limited (a=0.48 m). In order to characterize the geometry of zone, which includes the explosive atmosphere, the conic geometry has been chosen. According to IEC 31-35, cone angle (θ) has been assumed equal to 60°, whereas its height is equal to a (Figure 4). The cone vertex is turned upside-down, because biogas density (ρ_b) is greater than air density (ρ_a). The influence of release pressure variation on d_z, V_z and M_b is reported in Figures 5, 6 and 7. The release pressure (p_r) decrease from p_{max} to 0.8 p_{max} determines a more notable decrease of V_z (20.8 %) and M_b (21.4 %) than d_z (10 %).

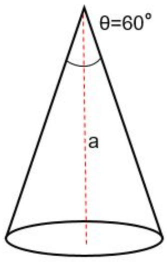

Figure 4: Geometry of Zone 2 (explosive atmosphere)

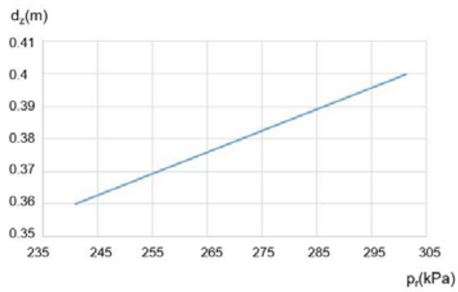

Figure 5: Trend of hazardous distance

Because of such pressure variation, d_z ranges between 0.36 m and 0.4 m, V_z between 0.76 m^3 and 0.96 m^3, whereas biogas mass flow ranges between 0.0011 kg/s and 0.0014 kg/s.

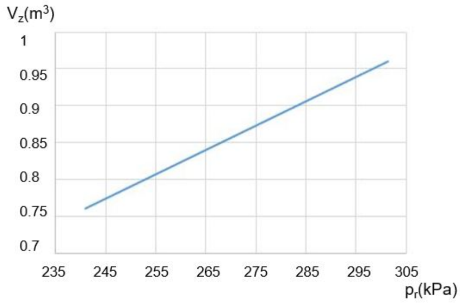

Figure 6: Trend of V_z

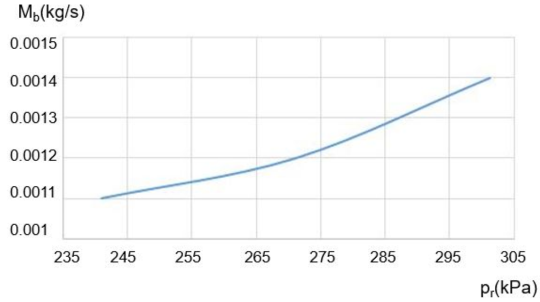

Figure 7: Trend of biogas mass flow

5. Conclusions

Biogas production is becoming an emerging industrial sector and therefore a particular attention has to be addressed to safety level improvement. The paper has described a methodological approach, which can constitute an efficient tool in support of technicians, who have to carry out the classification of zones, where potentially explosive atmospheres could occur. Hazardous areas classification should be carried out as an integral part of the risk assessment in order to identify the places, which require special precautions aimed at protecting the health and safety of workers. "Special precautions" mean precautions to control the potential ignition sources within the hazardous area, particularly in relation to the construction, installation and use of equipment. Additional data, referred to the process, which involves the dangerous substances, have to be taken into account, including the temperatures, pressures and workplace ventilation, because such parameters strongly influence the nature and extent of the hazardous place. In the indoor workplaces, a particular attention has to be addressed to the operating parameters (maximum air flow) of ventilation system in order to dilute the explosive mixture in extremely short times and decrease the extent of hazardous zones.

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