Evaluation and Mitigation of Risk Connected to Lighter than Air Gaseous Releases in Confined Environment

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1. Introduction

Notwithstanding the adoption of more and more accurate preventive techniques, hazardous release still represents a serious concern in the process industry. In particular, flammable release can give rise to the formation of flammable mixtures and, when an ignition source is available, to flash fires or even to explosions. Even if the application of Inherently Safer Technology principles is the best choice to achieve hazard reduction and prevent the effects of domino scenarios in process plants, this option cannot be fully applied in many contexts and the probability of the formation of explosive mixtures cannot be excluded at all. So the safe operation is accomplished by the application of active and passive strategies. The traditional safety approach has focused on adding protective measures and mitigation systems to the process to reduce the risk and improve safety. Mitigation of this kind of risk takes many forms and the most idoneous interventions depend upon different factors, e.g.:

- characteristics of the accident and of the equipment/plant section involved in the loss of containment (rupture/brake in a pipeline, hole in a storage vessel/ tank etc.);
- release definition (rate of discharge or quantity discharged) and hazardous properties of the involved materials (including physico-chemical characteristics and energy content);
- characteristics of the environment (confined, semi-confined, open air).

The main focus of protective measures is to limit the mass of the explosive mixture under formation within a threshold value corresponding to acceptable consequences in case of ignition. Clearly, the optimal strategy to cope with this target must be selected and designed according to the specific case under examination. In this paper, it is investigated the peculiar case of lighter than air flammable releases in partially confined environment, by developing ad-hoc an analytical dispersion model.

2. Theoretical

As well known, in case of gaseous releases in confined/semiconfined environment, the risk is connected to the potential build-up of a flammable mixture and to the possible evolving scenarios, namely fire and explosion. In order to set-up quantitative indications suitable to reduce the risk it is necessary to evaluate the maximum allowable accumulation in case of unwanted event (loss of containment) under the safety constraint. The appropriate evaluation of the consequences for man of the scenario is performed considering exposure to radiant heat (in case of flash-fire) and to

overpressure from blast wave (in case of explosion), taking into account proper threshold limits. Following measures can be considered and relevant parameters are to be calculated, so as to limit the gas accumulation:

- natural or forced ventilation, so as to obtain the dilution of the gaseous release, inherently preventing the build-up of dangerous concentrations;
- limitation of the release by means of periodic plant inspections and/or alarm and detection systems. In the following theoretical section, two basic situations can be sorted, mainly depending on the chemico-physical characteristics of the gaseous components and on the geometrical characteristics of the confined/semiconfined environment where the release occurs.

The general physical model we refer to consists of a release $\dot{V}_r$ occurring into a semiconfined volume V, from the ceiling of which a ventilation volume rate $\dot{V}$ exits, either by natural ventilation, through a venting area, or by a suitable forced ventilation unit. We can sort two basic scenarios, namely perfect mixing and gas stratification.

2.1 Perfect mixing scenario

A release of one gas component (e.g. H_2, CH_4, C_2H_2, C_2H_4 or CO) is supposed.
The molar balance of the component may be written as:

$$\frac{dV_r}{dt} = \frac{d}{dt}(Vy) = \dot{V}_r - \dot{V} \cdot y \tag{1}$$

where V_r= accumulated gas volume [m^3]; V=mixture volume [m^3]; $\dot{V}_r$ = release volume rate [$m^3 \cdot s^{-1}$]; $\dot{V}$ = ventilation volume rate [$m^3 \cdot s^{-1}$]; y= molar fraction of the component.

By integrating eq (1) under the condition $y(0)=0$, we obtain:

$$y = \begin{cases} \dfrac{\dot{V}_r}{\dot{V}} \left(1 - e^{-\frac{\dot{V}}{V}t} \right) & (\dot{V} > 0) & \text{(curve } a \text{ in figure 2)} \\[4mm] \dfrac{\dot{V}_r}{V} t & (\dot{V} = 0) & \text{(curve } b \text{ in figure 2)} \end{cases}$$

$$\tag{2a}$$
$$\tag{2b}$$

We assume the safety condition

$$y \leq y^* = V_r^* / V \tag{3}$$

where V_r^* is the critical volume of the accumulated gas, calculated on the basis of subsequent scenarios. The corresponding value of y^* is of the order 0.001, then the imposed safety constraint assures that the concentration in the gas mixture be well below the lower flammability limit (LFL) as $y^* << y_L$.

By analyzing the analytical expression of $y(t)$, following conclusions are drawn:

- if $\dot{V} \geq \dot{V}_r / y^* = \dot{V}_\infty$ equation (3) is respected;
- if, on the other hand, $\dot{V} < \dot{V}_\infty$, y reaches the value y^* at the time

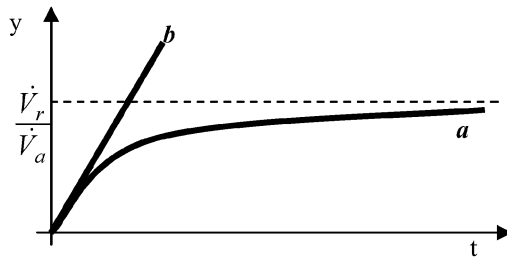$$t^* = \frac{V}{\dot{V}} \ln \frac{1}{1 - \dot{V}/\dot{V}_r} y^* \tag{4}$$

Figure 2: Time evolution of the molar fraction of a gas component [eqs (2a) and (2b)].
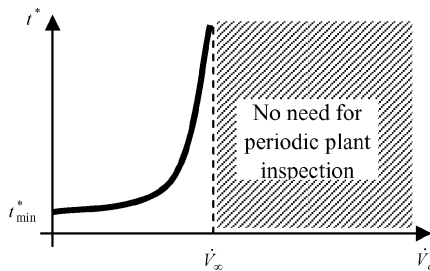

Figure 3: Time to reach the critical volume, as a function of the ventilation flow rate.

In this way, the respect of eq. (3) is not granted by ventilation only, so that other safety measures have to be considered, such as human inspections or automatic controls of the local with a frequency not lower than $1/t^*$. As shown in Fig. 3, this frequency must be increased as $\dot{V}_a$ decreases; in fact, it can be reduced down to the limiting value:

$$t^*_{min} = \frac{V}{\dot{V}_r} y^* \text{ , reached when } \dot{V} = 0 \text{ (eq. 2b).} \tag{5}$$

2.2 Stratification scenario

We assume that the release gas, due to its low density, accumulates near the ceiling of the building/enclosure, forming with air a layer volume V_s increasing as time goes on and characterized by an average concentration in the layer y_s.

We can distinguish following situations:

- Forced ventilation: $\dot{V} = const$

- Natural ventilation : $\dot{V} = \mu(2gh_s)^{1/2} A_v \ [m^3 s^{-1}]$

where: $\mu = \rho_a/\rho_s - 1 = (M_a/M_s)(T_s/T_a) - 1$; $h_s = V_s/A$ [m]; $\rho=$ density [kg m^{-3}]; $M=$ molar mass [kmol kg^{-1}]; $T=$ temperature [K] referred to air (a) or layer (s); $A_v=$ venting area [m^2]; h$_s=$ height of the layer [m], $A=$ area of the layer [m^2], usually corresponding to the ceiling area in the absence of "geometrical complications".

2.2.1 Forced ventilation

The volumetric balance referred to the gas component can be written as:

$$\frac{d}{dt}(V_s y_s) = \dot{V}_r - \dot{V} y_s \tag{6}$$

By integrating eq. (6), under the condition V$_s$(0)=0, we obtain:

$$V_s = \begin{cases} 0 & (\dot{V} \geq \dot{V}_r / y_s = \dot{V}_{s,\infty}) & \text{(7a)} \\ (\dot{V}_r / y_s - \dot{V})t & (\dot{V} < \dot{V}_{s,\infty}) & \text{(7b)} \end{cases}$$

When dealing with the situation described by eq. (7a), on one side no gas build-up can exist, as the venting flow rate is relatively high to avoid the formation of a concentrated gas layer. On the other side, the average gas concentration within the enclosure or building must anyhow respect the safety conditions imposed by the perfect mixing assumption and dealt with in the previous paragraph. Under the situation (7b), the volume of the gas layer increases linearly as time goes on. Generally speaking, the condition $y_s > y_L$ could be met, so that the only safety constraint is connected to the maximum allowable gas accumulation, V_r^*, and therefore to the accumulation of the mixture, V_s^*:

$$V_s^* = V_r^* / y_s \tag{8}$$

On combining eqs (8) and (7b), the minimum admissible duration of the accumulation is easily obtained:

$$t^* = \frac{V_r^*}{\dot{V}_r - \dot{V}y_s} \tag{9}$$

2.2.2 Natural ventilation
The volumetric balance referred to the gas component can be written as:

$$\frac{d}{dt}(V_s y_s) = \dot{V}_r = \mu' V_s^{1/2} y_s \tag{10}$$

where $\mu' = \mu A_v (2g/A)^{1/2}$ \hfill (11)

By integrating eq. (10), under the condition $V_s = 0$, we obtain:

$$t = \frac{2\dot{V}_r}{\mu'^2 y_s} \ln \frac{1}{1 - \frac{\mu' y_s}{\dot{V}_r} V_s^{1/2}} - \frac{2}{\mu'} V_s^{1/2} \tag{12}$$

The asymptotic value of the gas volume under stoichiometric conditions is:

$$V_{s,\infty} = \left[\dot{V}_r / (\mu' y_s) \right]^2 \tag{13}$$

Dealing with the here considered situation, the safety condition can be expressed as $V_s^* \geq V_{s,\infty}$ (volume corresponding to infinite accumulation time). Taking into account eqs. (8), (11) and (13), one can calculate the minimum venting area, $A_{v,\infty}$, required to meet the safety constraint, as follows:

$$A_v \geq \frac{\dot{V}_r}{\mu} \left(\frac{A}{2g y_s V_r^*} \right)^{1/2} = A_{v,\infty} \tag{14}$$

In analogy with the case of perfect mixing, if $A_v<A_{v,\infty}$, the safety can be achieved by added on control measures, i.e. human inspections or automatic controls, with frequency not lower than $1/t^*$, where t^* is easily calculated from eq. (12), by imposing $V_s = V_s^*$.

3. Results

As a numerical application of the model, the following situation is considered:
- hydrogen release within a building characterized by $V=1000$ m^3 , A=250 m^2;
- stratification scenario: $\dot{V}_r = 10^{-4}$ m^{3}s^{-1} ; $y^* = 10^{-3}$; $y_s=y_L=0.04$ (Lees, 2005).

The results are depicted in graphical form in Fig 4(a) and 4(b). It must be noticed that the model is easily adaptable to the evaluation of more general situations, e.g., complex geometrical conditions of the building; multi-component mixture of flammable gases.

4. Discussion And Conclusions

As a case-study, it is considered an industrial plant performing the dry distillation process of coal and addressed to the production of low grade (metallurgical) coke and foundry coke. The process is carried out by 4 parallel coke oven batteries, fed with fossil coal and heated by process coke gas conveniently desulphurized. The gas feeding section of each oven is localized in separated local beneath each battery (Fig. 5).
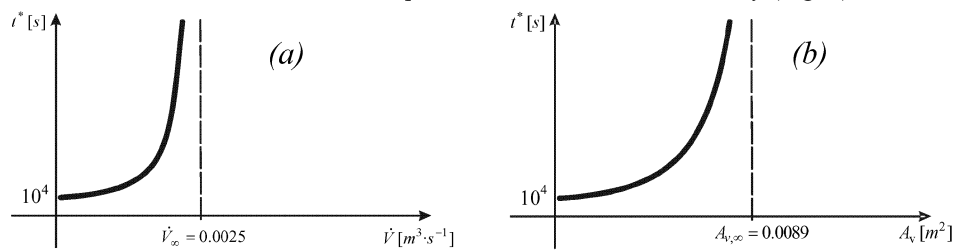

Figure 4: Minimum admissible duration of the accumulation for hydrogen, in case of forced ventilation (a) and natural ventilation (b).
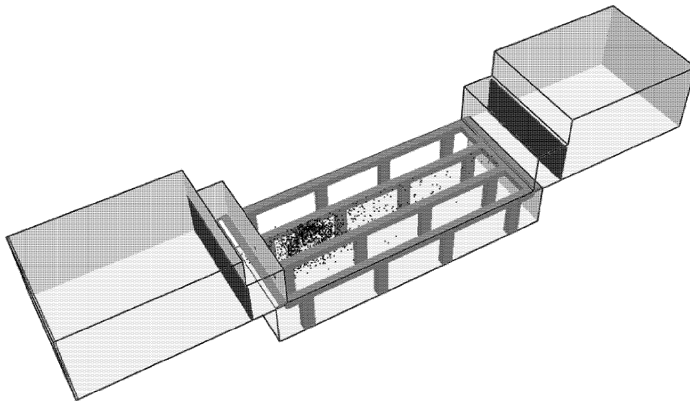

Figure 5: Schematization of the local beneath each coke oven battery.

Table 1: Mean composition of the feeding gas (referred to 10^3 moles of gas)

Component i	n_i	$-\Delta H_{c,i}$ (kJ mol^{-1})	$-\Delta H_c$ (kJ kmol^{-1})
O_2	2.9		
N_2	111.7		
CO_2	20.7		
H_2O	15.3		
CO	45.8	282.99	12961
H_2	536.5	285.84	153353
CH_4	230.7	890.4	205415
C_2H_4	20.7	1410.99	29207
C_2H_6	9.4	1559.9	14663
C_6H_6	4.41	3267.6	14416
C_7H_8	1.30	3909.9	5097
C_8H_{10}	0.39	4552.86	1792
C_5H_{12}	0.04	3509.5	127
C_6H_{14}	0.06	4163.1	252
C_7H_{16}	0.03	4816.91	126
C_5H_{10}	0.03	3919.9	122
C_6H_{12}	0.04	3290.9	123

The composition of the feeding gas is reported and calculated in table 1, corresponding to a combustion enthalpy of 437653 kJ kmol^{-1}. Experimental values of LFL and UFL were respectively obtained as 8 and 36% v/v. Making reference to the components of the gas mixture in the under oven buildings, according to the stratification scenario, it was possible to define required venting sections, assuming as conservative hypothesis LFL as target concentration. Furthermore, the periodic inspection frequency was defined as well as automatic alarm network, with proper intervention time and test interval. It can be noticed that in order to define the maximum build-up of gas the cautious assumption is connected to the stoichiometric concentration in the layer. The method allows determining the maximum spillage volume allowed, without ATEX certified equipment or classification. Risk reducing measures, including technical and organizational issues in different protection layers can be derived, on the basis of the quantitative approach here presented. Ideally, one should consider each measure according to norm ISO IEC 61511 (2003) and evaluate its reliability for example by determining its Safety Integrity Level (SIL), considering as well human factor with a proper quantitative human reliability assessment (Fanelli, 2010). As suggested elsewhere (Pasman, 2008), given possible uncertainty in QRA outcomes, owing to various contributing sources of uncertainty, the results here obtained were compared with CFD simulations, evidencing in this case, a fairly good agreement between the predictions of the two approaches.

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