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Analysis of the Flash-Fire Scenario in the Viareggio Accident

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On the 29th of June, 2009 the derailment of a rail-tanker containing liquefied petroleum gas (LPG) in the Viareggio station produced a large cloud of flammable vapours, which ignited in a flash-fire, causing 31 fatalities and extensive property damage. The literature models applicable to the simulation of flash fires differ for the hypothesis made and the complexity. The majority of models assume homogenous clouds, usually at stoichiometric concentration. However the dispersion of the substances released in accidental events frequently results in non-homogeneous stratified clouds. Computational Fluid Dynamics (CFD) models have limited applicability due to the large scale of the scenario, yielding extremely high computational burdens. Integral models based on empirical parameters are necessary for routine quantitative risk assessment practice, and more generally, for prevention and mitigation of the scenario.
In this study the models for simulating flash fires of stratified vapour clouds are applied to the study of the Viareggio accident. The model by Raj & Emmons was modified to include the correct description of the combustion of pre-mixed and diffusive flame. The considerations underlying the models by Feng and Kaptein & Hermance for flame velocity were implemented. The comparison with the actual outcomes of the accident, as recorded by an on-site survey, allowed for model validation.

1. Introduction

The structural failure of vessels containing pressurized flammable liquids leads to the release of large quantities of material in the surrounding environment. The vapours mix with air and, if ignited, may result in explosions (Vapour Cloud Explosion, Fuel-air Detonation) or burn in a Flash Fire (Cozzani et al., 2009). Modelling these scenarios is a complicated task: while Computational Fluid Dynamic (CFD) based on the Reynolds Average Navier-Stokes model allows for a simulation of the phenomenon, the presence of laminar combustion regimes as well as the scale required for a detailed simulation hinder the practical applicability due to an excessive computational burden. On the other side, simplified integral models, as the ones currently used in the practice of quantitative risk assessment, need sound validation.
A typical simplifying hypothesis, applied both in integral and CFD models, is to consider the fuel-air cloud as a homogeneous and stoichiometric mixture. The hypothesis is considered conservative, since stoichiometric mixtures are more reactive than real non-stoichiometric clouds. As a matter of fact, the dispersion of flammable liquefied gases in non-confined environments seldom results in homogeneous and stoichiometric mixtures. In reality clouds are usually rich in fuel closer to the ground level when vapour density is higher than surrounding air. Ignition of such clouds results in different combustion mechanisms depending on the concentration of the fuel-air mixture in different zones of the cloud.
The current study reviews the applicability of the Raj & Emmons model to the Viareggio accident. The observations on stratified flames by Feng et al. (1975) and Kaptein & Hermance (1977) are integrated in the model. The results are compared with the actual outcomes of the Viareggio accident.

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2. Models considered in the study

2.1 The Raj & Emmons Model

In spite of recent developments in CFD, the model for flash fire simulation more commonly applied is still the empirical correlation proposed by Raj and Emmons (R&E) in 1957 (CCPS, 2010). The model is based on experimental observations of pool fires and is able to describe the dynamics of both pool fire and flash fire scenarios. The model considers a two-dimensional flame geometry of height H and width W (Figure 1). The diffusive flame (fall of flame) propagates at constant velocity S [m/s] toward the unburned region of the vapour cloud, where fuel concentration in air is higher than the Upper Flammability Limit (UEL).
The R&E model considers a uniform concentration of the fuel-air mixture in the cloud. If fuel concentration is between the Lower Flammability Limit (LFL) and the stoichiometric ratio, the flame height (H, [m]) is approximately equal to the depth of the cloud (D, [m]). In fact, in this condition, no intake of air is required to sustain the combustion. On the other hand, if the mixture is rich in fuel, the flame entrains external air, generating turbulence, and the adiabatic expansion of the combustion products originates a flame plume higher than the initial cloud (H>>D). The application of conservation of mass, momentum, and energy over the plume results in a correlation between flame height and the upward velocity of gases u_0 at the flame base. The general prediction of u_0 is practically difficult. Therefore the R&E model assumes, on the basis of experimental observations, a linear correlation between flame width and height, the latter being double the width (H/W=2). As a result, the following correlation is proposed by R&E:

$$H = 20D \cdot \sqrt[3]{\frac{S^2}{gD}\rho'^2 \frac{wr^2}{(1-w)^3}} = 20D \cdot \sqrt[3]{\frac{S^2}{gD} \cdot \left(\frac{(1-\varphi)M_a + \varphi M_{fuel}}{M_a}\right)^2 \cdot \frac{w \cdot \left(\frac{(1-\varphi_{st})M_a}{\varphi_{st} M_{fuel}}\right)^2}{(1-w)^3}} \tag{1}$$

where g is the gravitational acceleration [m/s^2], φ is the fuel-air mixture mole fraction composition, M_a and M_{fuel} are the molar mass of air and fuel respectively [kmol/kg], the subscript $_{st}$ indicates the stoichiometric composition, and w is the inverse of the volumetric expansion due to combustion. If $\varphi > \varphi_{st}$ it is defined as:

$$w = \frac{\varphi - \varphi_{st}}{\alpha(1-\varphi_{st})} \tag{2}$$

where α is the constant pressure expansion ratio for stoichiometric combustion (typically 8 for hydrocarbons). If the cloud consists of pure hydrocarbon, w represents the inverse of the volumetric expansion resulting from constant-pressure stoichiometric combustion. If the mixture in the cloud is lean, the combustion occurs without elevating the plume: the flame height is equal to the cloud depth and w = 0.
It is worth noticing that the constant 20 in Eq(1) is extremely conservative when real cases are considered. Experimental observations on large scale showed the validity of Eq(1) with values of 10 for the constant in the case of GPL clouds (Rota et al., 1998).

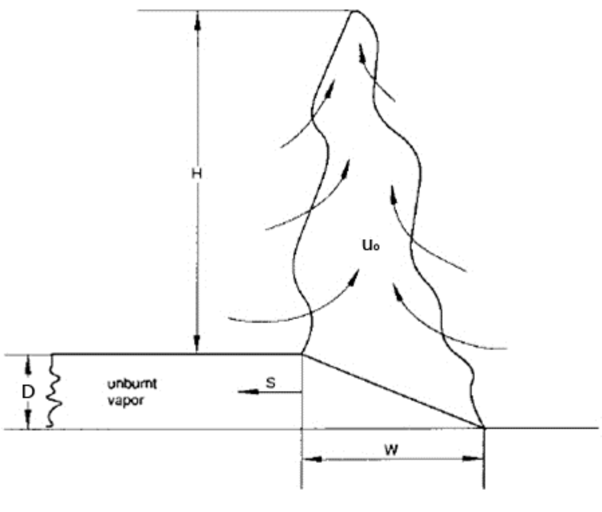

Figure 1: Schematic representation of the flame in Raj and Emmons model (adapted from CCPS (2010))

Another approximation in R&E model comes from the evaluation of the velocity of the flame front (S). Based on a few experimental observations Raj and Emmons proposed a linear correlation for S [m/s]:

$$S = 2.3U_w \tag{3}$$

where U_w is the wind speed [m/s]. More recently, an improved correlation was proposed (Rota et al., 1998):

$$S = 2.3 + 1.2U_w \tag{4}$$

The thermal effects of the flame are calculated from cloud composition and flame geometry. The latter is strongly influenced by cloud shape and the position of the point of ignition. The thermal dose experienced by an observer can be calculated as the integral in time of the contributions from a flat flame wall travelling across the cloud. Examples of such calculation are reported elsewhere (CCPS, 2010).

2.2 Proposed Models for Flame Velocity

The R&E model considers the formation of a cloud of homogenous concentration and depth. The reference concentration is equal to or greater than the stoichiometric ratio. Real clouds originating from pool evaporation or from the release of materials heavier than air are stratified clouds, with a vertical concentration gradient. These clouds tend to spread laterally (gravity spreading) rather than vertically. This configuration causes a behaviour of the flame different than the one considered in the R&E model. Fire in a stratified cloud of flammable vapours is characterized by the propagation of a pre-mixed flame in the zone of the cloud with concentration between LEL and UEL, followed by a diffusive flame on the limit between the stoichiometrically poor and rich zones of the cloud. Finally, if a zone with a concentration greater than UEL is present, a convective flame follows the other ones. This flame elevates above the cloud level due to the convective turbulence generated by the hot combustion gases, which promotes fuel-air mixing. The scheme proposed by Phillips (1965) and reported in Figure 2 describes the composition of the cloud with elevation and the different mechanisms of combustion in the case of a propane cloud.

The pre-mixed and convective combustion defines the extension and geometry of the flame front, but does not affect the velocity of the flame propagation, which progresses according to the mechanism in the pre-mixed flame zone. Feng et al.(1975) proposed a theoretical model for the behaviour of flame propagation in a layer of combustible mixture. They demonstrated, based exclusively on fluid dynamic considerations, that the stationary flame speed S [m/s] in a homogeneous layer converges into the values:

$$S = S_u \cdot E^{0.5} \tag{5}$$

where S_u is the laminar speed of flame [m/s] and E is the ratio of volume expansion between unburned mixture and combustion gases. Therefore the flame speed is not influenced by diffusive and/or convective combustion regimes. The correlation can be easily applied by considering that, in case of stratification, there is always a zone with composition quite similar to stoichiometric composition.

Kaptein and Hermance (1977) provided a more accurate prediction of experimental data by including in the model the potential energy and a parameter depending on the Froude number:

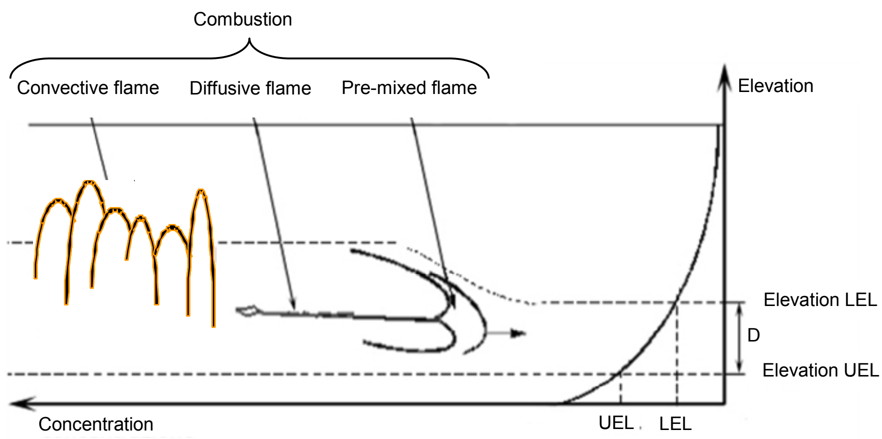

Figure 2: Composition of the layers and combustion mechanism (adapted from Phillips (1965))

$$\gamma = gD / S^2 \tag{6}$$

where g is the gravitational acceleration [m/s^2], and D is the height of the flammable layer [m].
Their solution for the velocity of the flame front (S, [m/s]) is therefore:

$$S = 0.5 S_u \left[\gamma + \sqrt{\gamma^2 + 4(1 + \rho' \gamma) E} \right] \tag{7}$$

where the variables are the same introduced in Eq. 1, 5 and 6.
Eq(7) yields the theoretical result obtained by Feng, Eq(5), for $\gamma = 0$.
The flame velocity values calculated by the relations above can be introduced in the R&E model, under the hypothesis that the propagation velocity of the flame is equal to the velocity of the flame in a homogeneous layer. It is worth noting that the effect of the depth of the flame layer is not included in the theoretical correlation by Feng. On the other hand, the inverse of the Froude number used in Eq(7) introduces the fluid dynamic effects of layer depth on the speed of the flame.
Tables 1 and 2 show results from the R&E model, accounting for different models of flame velocity. A stratified cloud of propane and a wind speed on 1 m/s were considered. The results in Table 1 refer to a homogeneous cloud, with depth D and concentration of 10%v/v of fuel in air. Table 2 considers a cloud of 3 meter depth, composed by two layers: an upper layer at stoichiometric concentration of depth D' and a lower layer at concentration of 10%v/v of fuel in air. The latter schematization of the cloud, defining a depth for the stoichiometric layer, allows for a more rigorous application of the Kaptein & Hermance model.

3. Application to the Viareggio case

On June 29th, 2009 at 23:48 a train, transporting liquefied petroleum gas (LPG), derailed at the Viareggio station in Italy, due to a mechanical failure of an axle. One of the derailed railway tanks tilted, was punctured and released about 46 metric tons of LPG. A vapour cloud denser than air spread over the railway area and into the nearby roads. Cloud ignition in a unknown point, some 100÷300 seconds later, resulted in a large flash fire, which caused 32 fatalities and severe damage to the nearby area.
Figure 3 shows the area affected by the flash fire. Landucci et al. (2011) carried out an inspection of the affected area on July 3rd, 2009. The damages recoded in this survey are summarized in Figure 3.
The level of damages was classified in 3 severity classes:

- Radiation exposure: damages from thermal radiation, without flame impingement (e.g. deformed plastics, minor damages to vegetation);
- Moderate damage: evidence of flame impingement; damaged vegetation, minor damage of buildings;
- Severe damage: severe damage to vegetation, buildings, vehicles, etc.

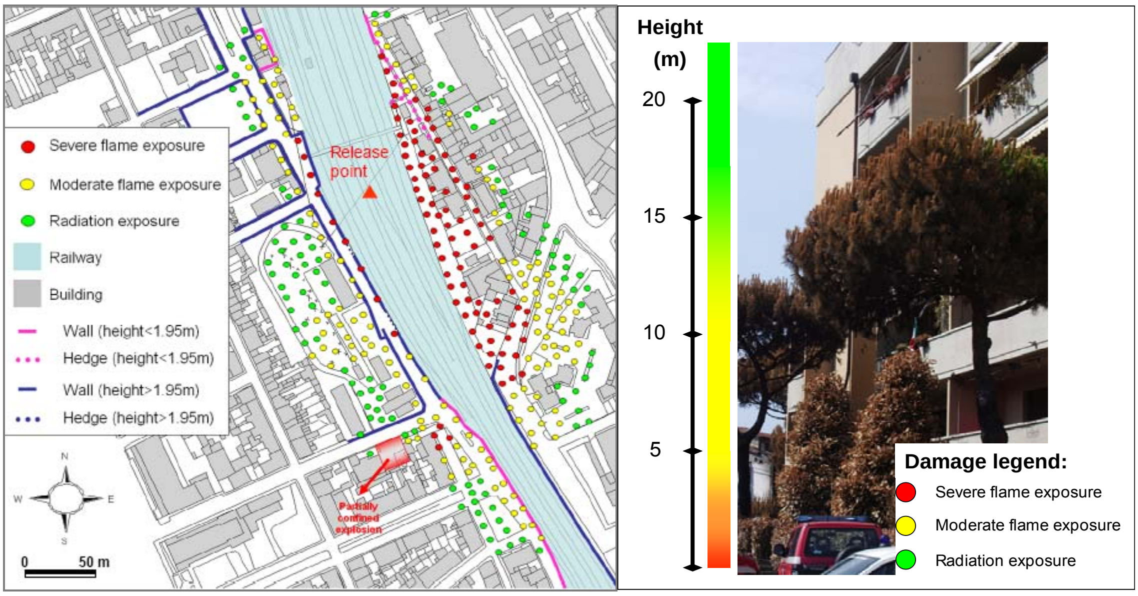

Figure 3: Left panel: damage map of Viareggio accident. Right panel: vertical profile of the damage in a road east of the railway stations. Adapted from Landucci et al. (2011).

Table 1: Flame height (m) in a cloud of depth D and fuel concentration 10%v/v as calculated according to the R&E model and different hypothesis on the flame speed. U_w = 1 m/s, S_u = 0.44 m/s, E = 8. For the application of Kaptein & Hermance a thin layer (depth 0.01 m) at stoichiometric concentration was considered above the cloud.

D, m	H, m Rota et al., Eq(4)	H, m Feng, Eq(5)	H, m Kaptein & Hermance, Eq(7)
0.40	8.27	4.35	4.46
0.80	13.30	7.07	7.24
1.20	17.57	9.42	9.64
1.60	21.44	11.56	11.82
2.00	25.02	13.55	13.86

Table 2: Flame height (m) in a two layer cloud of overall depth D=3 m. Upper layer (depth D') at stoichiometric concentration and lower layer (depth D-D') at fuel concentration 10%v/v. Flame height (H) calculated at according to the R&E model and different hypothesis on the flame speed (S). Uw = 1 m/s, S_u = 0.44 m/s, E = 8

D, m	H, m Rota et al., Eq(4)	H, m Feng, Eq(5)	H, m Kaptein & Hermance, Eq(7)
0.40	20.53	16.36	21.47
0.80	19.48	14.51	20.85
1.20	18.32	12.57	19.17
1.60	17.03	10.51	16.78
2.00	15.50	8.28	13.75

Table 3: Flame velocity (S) and height (H) for cloud parameters similar to the Viareggio accident. Values calculated by R&E model and other models for flame velocity considering two alternative schematization of the cloud. Uw = 1 m/s, S_u = 0.44 m/s, E = 8.

I - Homogeneous cloud			
Depth of the flammable layer (m)	2.28		
Average concentration (v/v)	0.10		
Model used for S	Rota et al., Eq(4)	Feng et al., Eq(5)	Kaptein & Hermance, Eq(7)
S (m/s)	3.14	1.24	1.29
H (m)	25.65	14.89	15.22
II – Stratified cloud (two homogenous layers)			
Depth layer I (m)	1.24		
Concentration layer I (v/v)	0.10		
Depth layer II (m)	1.04		
Concentration layer II (v/v)	0.05		
Model for S	Rota et al., Eq(4)	Feng et al., Eq(5)	Kaptein & Hermance, Eq(7)
S (m/s)	3.14	1.24	2.98
H (m)	16.81	9.64	16.28

No overpressure effect was recoded outdoor. This confirms the flash-fire nature of the scenario that occurred. Moreover, the stratification of the cloud is indirectly proven by the severity of the observed damages: they suggest an intense and relatively long exposure to flame, which is typical of convective/diffusive flame scenarios with moderate flame velocities.

The extension of the burning cloud at the moment of ignition may be estimated as the area in Figure 3-left, where severe damages were recorded. The damage level out of this area decreases quickly with the distance: the moderate damage and radiation exposure regions constitute the flame border.

The right panel of figure 3 shows the vertical profile of damages. The average height of the buildings in the area is about 10m. Severe damages were observed up to 10 m of elevation. Damages typical of distant radiation were recorded only at elevations larger than 15m.

A CFD simulation of the cloud dispersion is reported by Pontiggia et al. (2011). This kind of simulation allowed for the evaluation of the vertical profile of the dense spreading cloud in several points and at different times. The section of the cloud with concentrations greater than LEL at the estimated time of ignition was found to be between 2.2 and 2.5 m. The cloud was highly stratified, presenting a distinctive

gradient of concentration with elevation. The depth of the zone with concentrations greater than the stoichiometric ratio was evaluated to be around 1.9 m in the central points of the cloud and 0 m in the peripheral points, with a clear stratification in all the intermediate points.
Table 3 reports the results obtained by the models discussed above, considering a point in the central zone of the vapour cloud where significant stratification was present. Similar to Tables 1 and 2, two schematizations of the cloud are reported in Table 3: a single homogeneous layer cloud and a two-layer cloud. The results in Table 3 show that the use of different models for flame velocity generate moderate differences in the evaluation of the scenario, both for flame propagation and for flame geometry. In particular the Kaptein & Hermance model, coupled with a two-layer stratification of the cloud, provides a more realistic value of the flame velocity and, once applied to the R&H model, of the flame height. A fundamental characteristic of this model is the independence of wind velocity. For the Viareggio accident, the weather conditions at the moment of the accident were such that wind speed was extremely low (less than 1 m/s). These conditions are difficult to describe using models like the ones in Eq(3) and (4). Also the Feng model, which is a particular case of Kaptein & Hermance model, does not account for wind speed; therefore this simplified approach leads to less realistic results.
When compared to the observed consequences of the Viareggio flash fire, all of the proposed models produce conservative results, confirming their validity within the hypothesis made. The use of correlations based on fluid dynamic considerations, rather than on empirical correlations, is confirmed as a promising route for the development of more advanced models for the description of flash-fire scenarios involving stratified clouds.

4. Conclusions

The accident that occurred in Viareggio, Italy on June 29th, 2009 clearly shows the severity of flash fire scenarios from the release of large quantities of flammable materials in densely populated areas. The availability of reliable models for the analysis of such scenarios is of utmost importance in quantitative risk analysis of hazardous material transportation. Up to date, the Raj & Emmons model is the only model practically applicable to the evaluation of the flame geometry in flash fire scenarios. The model requires the evaluation of the velocity of flame propagation in the vapour cloud. The empirical correlations typically available, based on wind velocity, were compared to alternative correlations based on fluid dynamic considerations. The application of such correlations to the cloud conditions of the Viareggio accident lead to results compatible with the observed consequences. The model by Kaptein & Hermance is identified as particularly appropriate to describe the flame propagation in the weather conditions of the accident, where wind velocity was almost negligible.

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