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Flash Fire: Historical Analysis and Modeling

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Among major accidents, different types of fire can occur: pool fire, jet fire, flash fire or fireball. A flash fire is the combustion of a vapor cloud resulting from the escape of a flammable material, which after mixing with the air reaches an ignition source. This paper provides an overview of flash fires, which are rather poorly known when compared to other types of fires. Although these events have a relatively short duration, they are capable of producing high levels of radiation.

In order to determine the significance of this phenomenon, a historical analysis of accidents involving flash fire has been carried out. 176 accidents have been analyzed, most of them taken from MHIDAS database. The causes, substances involved and consequences on the population are reported. The sequences of accidents involving a flash fire have been also analyzed. In addition the diverse aspects related to flash fire modeling are commented and the few models proposed by different authors are analyzed.

Historical Analysis

For a better understanding of flash fires, the most frequent causes and consequences associated to the ignition of a flammable vapor cloud should be known. To cover this gap, a historical survey was performed by using information contained both in the database MIDHAS and in other sources of information. Due to the fact that not all accidents are reported in the databases and furthermore the accidents descriptions are often rather reduced, this type of analysis is subjected to some restrictions.

Origin of the accidents and material involved

Of the 176 accidents found in the survey, the origin was known in 99.4% of cases. Most of the accidents occurred in process plants (35.8%), followed by those occurred in transport (26.1%), storage (19.3%) and loading/unloading operations (14.2%). Liquefied petroleum gas was the substance most frequently involved (41% of cases).

General causes of the accidents

Mechanical failure was the first general cause of accidents, with 44.3% of the cases, followed by those due to human error (36.9%). Among those originated by human error the specific causes were those related to general maintenance (18.8%), general operations (14.5%), procedures (13%), overfilling (13%) and design (7.2%).

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Population affected by the accidents

With respect to the population affected, three categories were taken into account: deaths, people injured and people evacuated. Concerning the number of deaths, Figure 1 shows the distribution found for the 124 accidents for which this information was available. The values obtained from the selected records and their cumulative probabilities have been plotted in Figure 2, where *N* is the number of deaths and $P(x \geq N)$ is the probability that in an accident the number of deaths be $\geq N$. The experimental points follow approximately a straight line with a slope of -0.77, indicating that the probability of an accident with 10 or more deaths is 6 times greater than one with 100 or more fatalities.

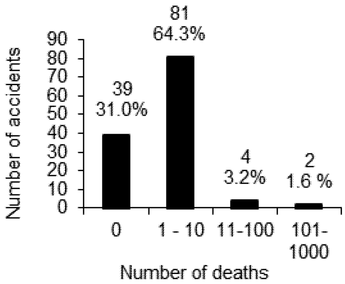

Fig.1. Number of deaths in flash fires

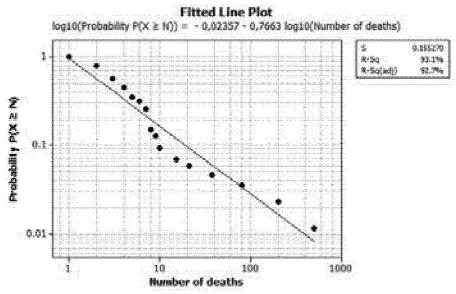

Fig.2 Accumulative probability with N deaths

In 75% of accidents information on the eventual occurrence of injured people was available: in 62.9% of cases there were 1-10 injured, in 19.7% of cases there were no injuries, and only 3.8% of cases recorded 101-1000 injured. 19.3% of accidents had information on the number of evacuees; in most accidents there were not evacuees, while in 17.6% of cases the number of evacuees ranged from 101 to 1000.

Accidental scenarios

To analyze the probability of occurrence of accidental scenarios involving flash fires, the relative probability event tree has been constructed (Figure 3). The number of accidents and the relative probability (the ratio of the number of accidents in a level and the number of accidents in the previous level) of occurrence are represented in each branch.

Most of accidents (96 %) start with a loss of containment, the rest being initiated by an explosion or another accident. The most common scenario (63.6% of cases) is an initial release of flammable material giving rise to a vapor cloud that subsequently ignites as a flash fire; in most of these cases no additional major accidents occurred.

Nevertheless, in a third of the registered accidents there was an escalation in the consequences after the flash fire. The most frequent sequence of events (24.3 %) corresponds to flash fire followed by one or more explosions.

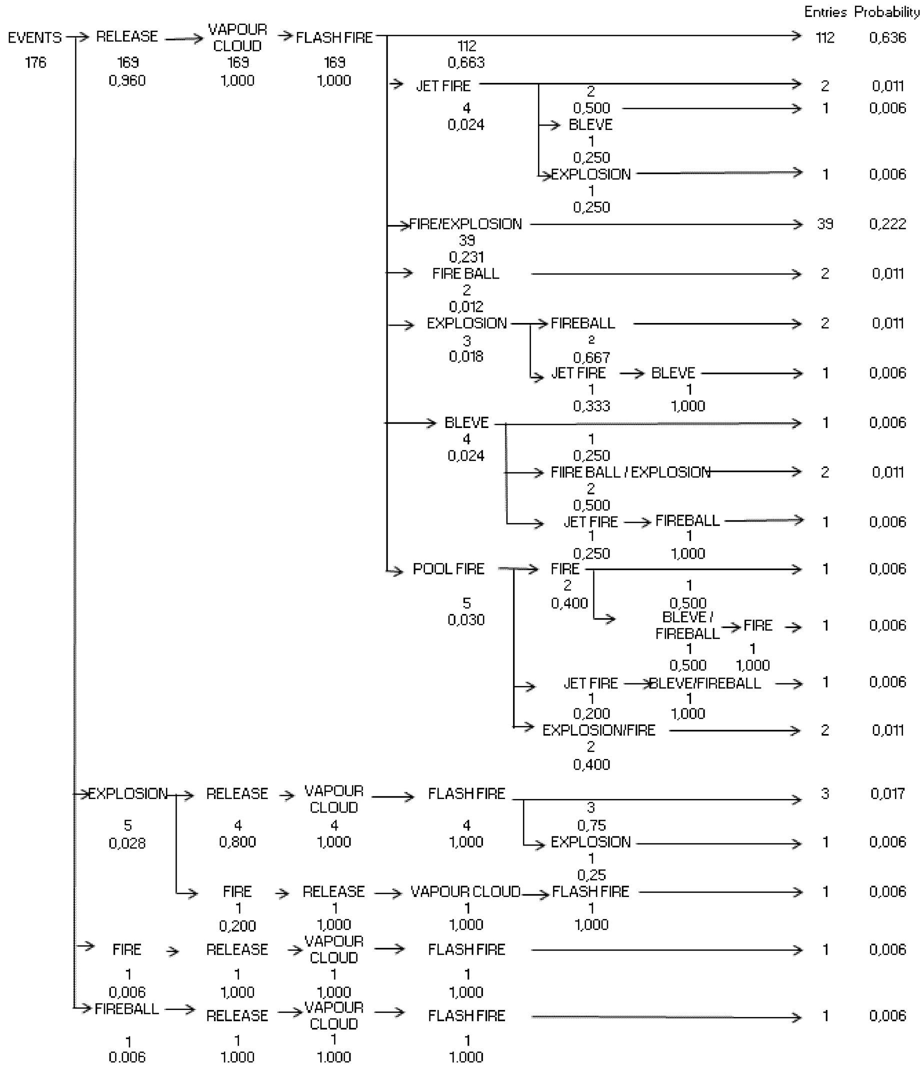

Fig.3 Event tree

According to the event tree, if there is a flash fire the probability that another major accident occur is 0.33; the probability that this second accident be an explosion/fire is 0.24. And finally, the probability that a flash fire is the last event in a sequence of accidents is almost negligible (0.03).

Mathematical Modeling

In this section the most common models are analysed and commented. Rather few mathematical models have been proposed for flash fires as compared to other types of fires; furthermore, the number of experimental studies is also very reduced, due to the difficulty found in such experimental work; one of them are specially interesting: the Coyote series of tests (LLNL, 1983) conducted to determine the features of fires resulting from the ignition of dispersed vapor cloud of LNG.

Einsenberg et al. (1975) and Fay & Lewis (1976)

The simplest models are based on the assumption of Gaussian atmospheric dispersion to estimate the fuel concentration within the cloud and the cloud size.

Einsenberg et al. (1975) assumed that the cloud shape is a half ellipsoid. The thermal radiation model used is based on the Stefan-Boltzmann equation; this is a problem as temperature is difficult to estimate due to its large variation (Lees, 2005). The model estimates the volume and area of radiation, assuming that the combustion process is not intense and that the burning is controlled by buoyancy (CCPS, 1989) to simplify the calculation process.

Fay and Lewis (1976) developed a model based on small scale experiments for non-steady burning of unconfined fuel vapor clouds, giving expressions to calculate the maximum diameter, height and time required for complete combustion. The correlations were validated by experiments with up to 200 cm^3 of methane, ethane and propane. The model assumes that the turbulent diffusion flame is a fireball (Mudan and Croce, 1988). However, experiments conducted with propane do not show evidence of a fireball; there is general agreement from field experiments in that a flash fire does not become a fireball except for the unusual situation that would arise from a massive release of fuel gas together with an ignition immediate.

Raj & Emmons (1975, 2007)

One of the most widely used and cited, has its origin in another one previously developed by Stewart for pool fires. It is based on the following assumptions (Mudan and Croce, 1988):

1. - The geometry of the fuel vapor cloud is two dimensional.
2. - The combustion is controlled by natural convection.
3. - The flame propagation velocity with respect to the unburned gases is constant.

From experimental observations the relationship between the visible flame height H and flame base width W was found to be $H/W = 2$. From this empirical fact it is possible to relate the visible flame height to burning velocity S through a mass balance for the triangular area bounded by the flame front and the flame base (CCPS, 1989). This results in an approximate, semiempirical expression:

$$H = 20d\left[\frac{S^2}{gd}\left(\frac{\rho_0}{\rho_a}\right)\frac{wr^2}{(1-w)^3}\right]^{1/3} \quad (1)$$

Here the number 20 corresponds to an empirical coefficient originally obtained from pool fire data (laboratory-scale experiments). The empirical expression that relates the flame speed (with respect to unburnt gas), S, with the wind speed, U_w, obtained from field scale data, is $S = 2.3U_w$. More recently another correlation has been proposed: $S = 0.8+1.6U_w$. This was obtained from a series of real scale experiments conducted for LNG vapor clouds between 1968 and 1984 (Raj, 2007). Moreover, the burning rate is assigned as proportional to wind speed; thus, under stable atmospheric conditions burning velocities would be extremely small and flash fire duration proportionately long, which is clearly different from reality. These correlations assume that flame propagation velocity is proportional to the wind, and do not consider the dispersion and the influence of ground roughness, heat transfer to the cloud or turbulence induced by the way leakage.

One of the uncertainties in this model is the assumption of homogeneous concentration, as in a real case the composition varies continuously through the cloud. Another point in question concerns the entry of air into the plume, which is assumed to be controlled by natural convection, a fact that minimizes the difference between the gas density in the plume and the ambient air density, whereas in fact the heat of the fire makes the plume density to be significantly smaller than the environmental one. Finally, flame geometry relies on empirical correlations based on small scale experiments using pure fuel rather than fuel-air mixtures.

Cracknell and Carsley (1997)

The model calculates the height of the flame, assuming that the flame height at a given position is related to the mass of flammable material in the cloud at that point. The model is based on the following assumptions:

- The products of combustion vent only vertically.
- Each mole of flammable material carries a stoichiometric amount of air.
- The mixture burns at the adiabatic flame temperature.

This model does not take into consideration issues such as the concentration profile through the vapor cloud or parameters affecting the dispersion. Furthermore, it does not take into account the influence of turbulence, as generated by obstacles, on flame speed. The flame through a flash fire is turbulent, as shown by the experiments with propane which gave average flame speeds of up to about 12 m /s (Mizner and Eyre, 1982).

Kumar et al. (2001)

Kumar et al. (2001) developed a numerical model to predict the maximum flame height based on an extension of the work by Raj and Emmons (CCPS, 1994). It calculates the flash fire plume width, the flame speed in the vertical direction and the difference between ambient density and plume density on the plume axis. The model incorporates wind speed, temperature, density and different atmospheric stability classes. The results of the numerical model have been compared with those from the analytical model quoted in CCPS: the maximum flame height values predicted by CCPS are much higher than the maximum flame height predicted by the numerical model in similar conditions.

This model assumes:

1. - A two dimensional geometry.
2. - The combustion of the flammable cloud is controlled by natural convection.
3. - The depth of the vapor cloud is small compared with the height of the flame.

Some of the uncertainties of this model are the assumptions of uniform concentration and that the combustion of the flammable cloud is controlled by natural convection; these hypotheses rely on considering and idealized situation, in which a planar flame front spreads horizontally through a uniform vapour of finite depth and fixed molar concentration on the ground.

Conclusions

The historical survey has shown that most flash fires occur in process plants (36%). The main cause of flash fires is mechanical failure (44%), being the most common failure the overpressure. The most frequent scenario (64% of cases) is an initial release of flammable material originating a vapor cloud that subsequently ignites. In 33% of accidents there is an escalation of consequences after the flash fire. The most frequent sequence (24% of cases) is a flash fire followed by a series of explosion/fire.

The scarce experimental studies and models of flash fires have been reviewed by very few authors over recent decades. There are few models, being the most widely used the one developed by Raj and Emmons. However, all these models have significant limitations and areas of uncertainty.

Flash fires are still poorly known, being this partly due to the difficulty found in experimental work. Therefore, research is necessary in aspects such as flame shape and size, estimation of view factors and emissive power, and dependence of flame speed on cloud composition, wind speed and ground roughness.

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