

MAIN FEATURES AND MATHEMATICAL MODELLING OF FLASH FIRES

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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 can originate high thermal radiation intensities.

The experimental tests carried out by several institutions, mainly with liquefied natural gas and liquefied propane gas, have contributed to a better understanding of the phenomena involved in the formation of a flammable vapor cloud and its subsequent ignition. However, the number of experimental studies is very reduced, due to the difficulty found in such experimental work, and many aspects of flash fires are still poorly known.

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 data show that most of the accidents were originated in process plants. The different causes, the substances involved and the consequences for the population are also reported in this paper. The sequence of accidents involving a flash fire has been analyzed using relative probability event trees.

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 different databases 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. This is especially true for the release of relatively small amounts of flammable material or in those cases where the extent of the damage is negligible.

In this historical analysis MHIDAS database was the most important source of information and the database of reference. The Major Hazard Incidents Data service (MHIDAS) is a database developed and managed by the Safety and Reliability Directorate (SRD) of the UK Health and Safety Executive (HSE); it contains accidents from over 95 countries since the beginning of the 20th century up to 2007 and all the information on the MHIDAS database is taken from public sources.

Other information sources have been also used such as the database ARIA (Analyse, Recherche et Information sur les Accidents), the Chemical Safety Board (CSB) and diverse bibliographical sources.

In order to identify the records specifically related to accidents that involved a flash fire, it was necessary to search in the databases by the keyword "flash fire", obtaining 134 records. The research was also conducted looking for others keywords such as "vapour and cloud and fire", obtaining 142 records. Accidents were analyzed according to the description fixed by the databases, classified and selected. A total of 176 accidents involving a flash fire were finally selected. One of the criteria used to select the accident was that it had to be clear that there had occurred a release of a liquid or vapor followed by its ignition.

Origin of the accidents

MHIDAS classifies the origin into two categories: general and specific. The general origin field designates the place or main activity where the accidents took place (process, storage, transport, transfer, waste, domestic/commercial and warehouse), whilst the specific origin describes the conditions surrounding the accident described in the general origin field. Of the 176 accidents found in the survey, the origin was known in 99.4% of cases. In Figure 1, the distribution of the diverse origins of the accidents is presented. 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%). These values are slightly different from those obtained in an extensive survey of all major accidents (Vilchez et al, 1995; 5325 cases), in which transportation was the first origin (39%) and process plants the second one (24.5%); as for storage and loading/unloading, the frequencies were similar.

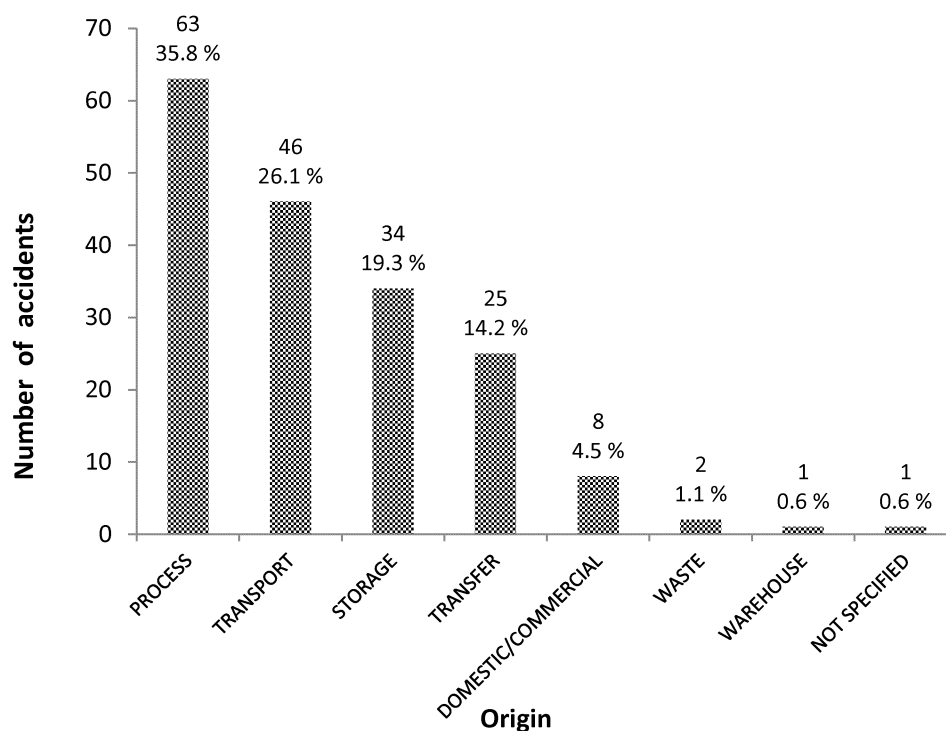


Fig.1. Origin of flash fires.

With regard to the specific origin of the accidents, Table 1 shows the distribution of the main contributions to accidents in process plants, loading and unloading, transportation and storage of materials.

The analysis of these data shows that in the process plants most accidents occur in process vessels, with 36.7% of cases. These vessels include units such as reactors, distillation columns, etc. The second place is taken by accidents arising from pipes (22%). It is important to note the significant equipment and piping layout in most process plants, with a series of elements -flanges, connections- prone to a potential loss of containment.

In terms of accidents in the transportation of materials, again pipes (pipe-lines in this case) are the equipment that appear most frequently (47%). The road (36%) and rail (8%) transport have also an important contribution.

Table 1: Specific origin of the accidents involving flash fire

Specific origin	No. of accidents	% of category	% of total
<i>Process</i>			
Process vessels	22	36.7	13.2
Pipework	13	21.7	7.8
Reactor	10	16.7	6.0
Not specified	9	15.0	5.4
Others	6	10.0	3.6
<i>Transport</i>			
Pipeline	22	46.8	13.2
Road tanker	17	36.2	10.2
Rail tanker	4	8.5	2.4
Ship	3	6.4	1.8
Tank container	1	2.1	0.6
<i>Storage</i>			
Atmospheric pressure vessels	15	42.9	9.0
Pressurised storage vessels	12	34.3	7.2
Pipework	4	11.4	2.4
Not specified	2	5.7	1.2
Process vessels	1	2.9	0.6
Road tanker	1	2.9	0.6
<i>Transfer (loading/unloading)</i>			
Hose	8	32.0	4.8
Pressurised storage vessels	4	16.0	2.4
Road tanker	3	12.0	1.8
Pipework	3	12.0	1.8
Others	7	28.0	4.2

Regarding accidents in the storage area, the highest frequency occurred in storage tanks at atmospheric pressure, with 42.9% of the accidents in this category, followed by the pressure storage vessels (34%) and again by pipes (11%). Finally, 14% of accidents occurred in loading and unloading of materials, an operation which is certainly potentially dangerous. In this category, it is significant that 32% of accidents occurred in hoses; although they are very practical and widely used, it is well known that they are more frail and delicate than the fixed pipes.

Material involved

With regard to the type of material involved in the accident, it has been found that liquefied petroleum gas (LPG) was the substance most frequently involved (41% of cases), followed by gasoline (6.3%), crude oil (6.3%) and vinyl chloride (4.0%). Moreover, a large percentage (30.7%) corresponds to the sum of different hydrocarbons.

General causes of the accidents

The MHIDAS data base considers eight general causes of accidents: mechanical failure, impact failure, human factor, instrumental failure, service failure, violent reaction, external events and upset process conditions.

The distribution of general causes can be seen in Figure 2; the mechanical failure was the first general cause of accidents with 44.3% of the cases, followed by those due to human error (36.9%). It should be mentioned that the causes are unknown for 17% of accidents. As the accidents can have more than one cause, the sum of percentages is not equal to 100; this happens also with the specific causes.

Amongst the accidents due to human errors, the most frequent specific cause is that related to general maintenance (18.8%), followed by general operations (14.5%), procedures and overfilling with the same percentage of 13%, and finally by design (7.2%).

In the category of mechanical failure, the specific cause is not known for 23% of the accidents, whereas the most frequent specific cause is the failure by overpressure with 13% of cases, followed by an equal percentage of 12% for flange coupling failure and failure in valves.

It is also interesting to mention that the 14.8% of the rest of the accidents correspond to failures by impact, followed of the 12.5% by external events, violent reactions (3.4%) and those due to others causes (6.3%).

Regarding the impact failure, the main cause is by accidents in highway in which other vehicles are not involved (30.8 %), followed by the accidents in which another vehicle participated (23.1%). Finally, considering the external events, the most important ones are fires, with 35% of the total of this category.

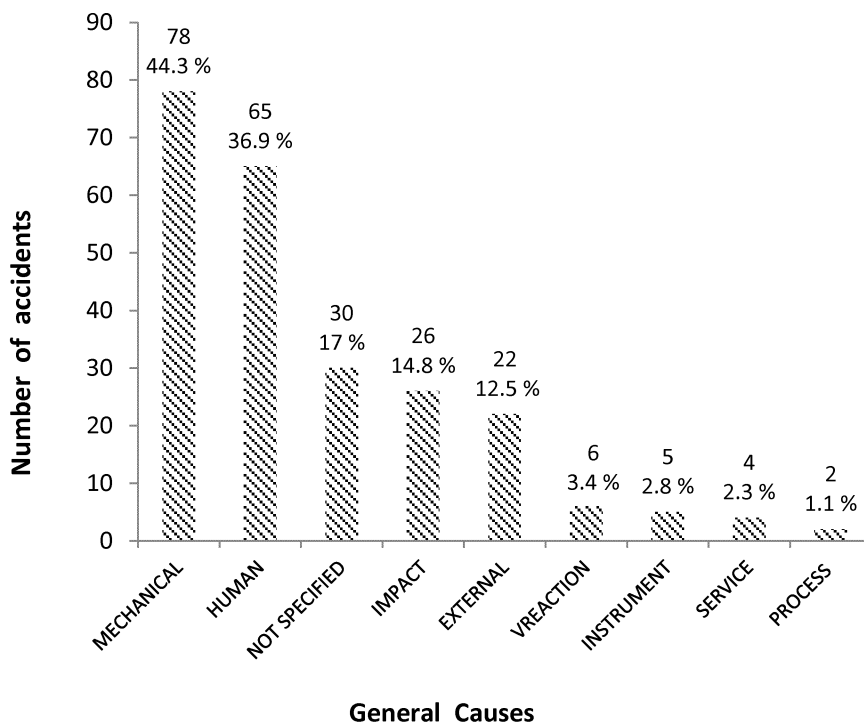


Fig. 2. General causes of flash fires.

Population affected by the accidents

With respect to the population affected by accidents, they are classified into three categories according to the scale of the consequences: number of deaths, numbers of people injured and number of people evacuated.

Concerning the number of deaths, Figure 3 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 4, 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.

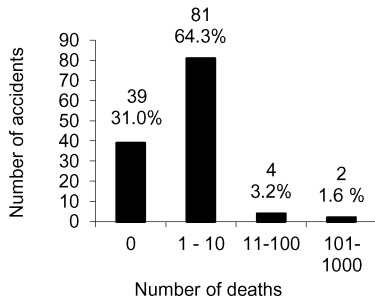


Fig. 3. Number of deaths in flash fires.

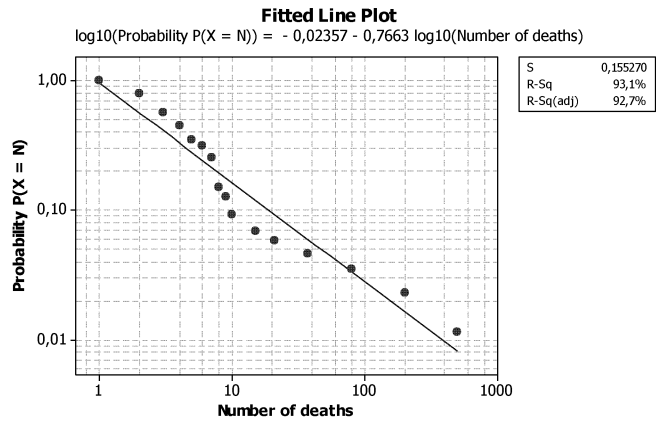


Fig. 4. Accumulative probability with N deaths.

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 people injured. 19.3% of accidents had information on the number of evacuees; in most accidents there were not evacuees, whereas in 17.6% of cases the number of evacuees ranged from 101 to 1000.

Accidental scenarios

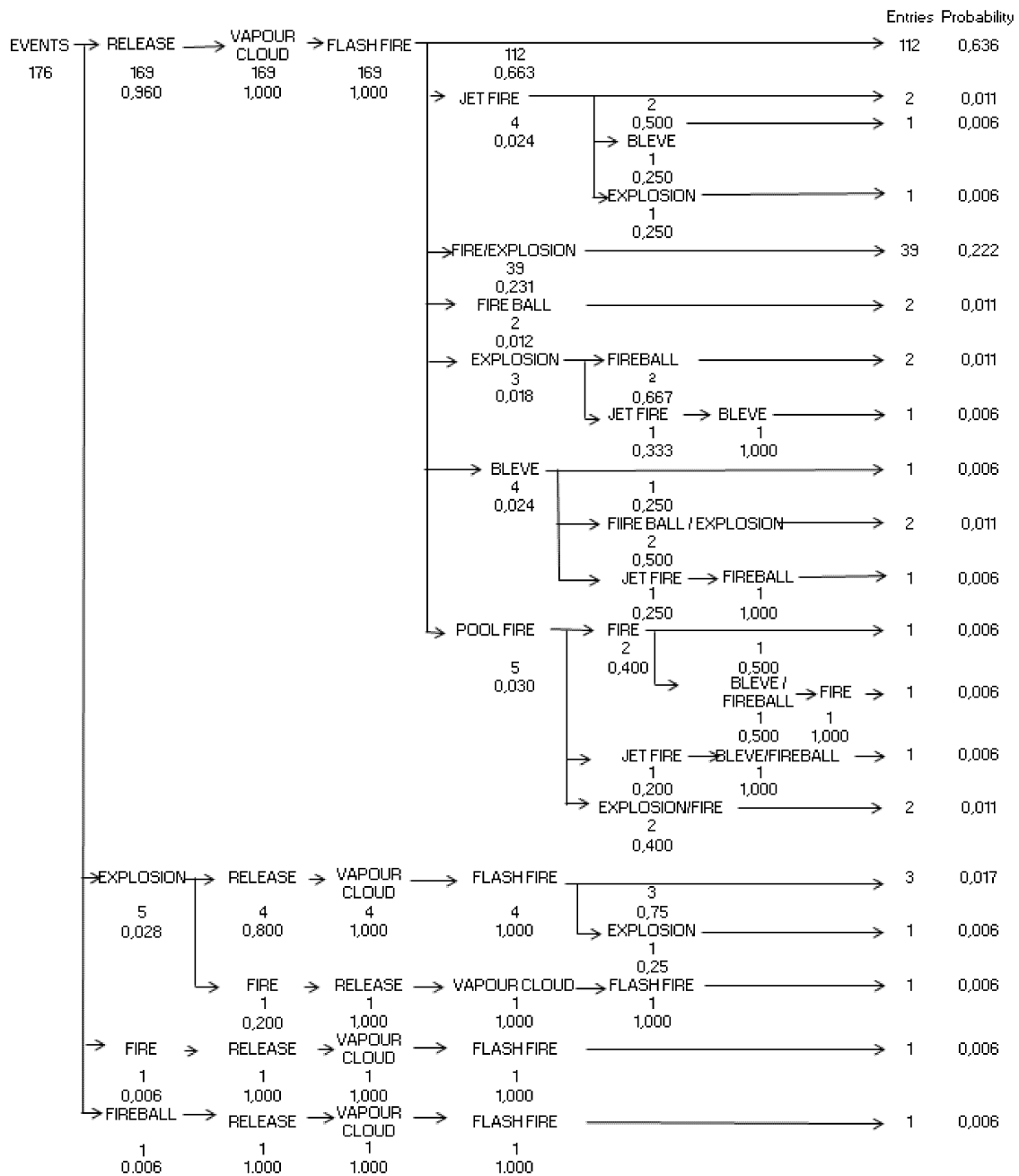
With the aim of presenting a scheme of the probability of occurrence of a series of accidents in which flash fires have been involved, a tree of events has been elaborated (Figure 5). The number of accidents and the relative probability of occurrence are represented in every branch. This relative probability is obtained from the division of the number of accidents in a given level and the number of accidents in the previous level.

Of the studied accidents, most of them (96 %) started with a loss of containment, followed by 2.8 % that were initiated by an explosion and, finally, 1.2 % begun with a different accident. The most common scenario, with 63.6% of cases occurred when after the initial release of flammable material, a vapor cloud was generated which was subsequently ignited causing a flash fire. In most of these cases the fire lasted a relatively short time, without the generation of any other major accident.

Nevertheless, in a third of the registered accidents there was an escalation in the consequences after the flash fire. The most frequent succession of events, with 24.4 %, corresponds to the cases where after the flash fire, the fire was followed by one or several explosions; for example, in Texas, 1968, the fire managed to spread up to approximately 65 acres involving several small tanks of a process plant originating subsequent explosions.

In 2.84% of the cases, after the flash fire a pool fire occurred, and this was followed by major accidents such as fires, jet fires, explosions or BLEVE. This happened in a refinery in Texas in 1978, where the domino effect spread in a cascade of accidents: flash fire → pool fire → BLEVE/fireball and fire, repeating the sequence of BLEVE/fireball and fire in other processes units.

Another sequence of events found in 2.4% of the cases is the one corresponding to a flash fire followed by a BLEVE. A case that followed this pattern happened in the refinery of Feyzin in 1966, where after the flash fire a series of BLEVES happened.



MATHEMATICAL MODELLING

With regard to the existing data, it has been found that the number of large-scale quality field data sets for flash fires is rather limited. This type of experiments is expensive to carry out, and it is therefore limited in terms of the number of experimental trials; Table 1 shows the most significant experimental programs.

Table 1: Summary of vapour cloud fire data sets

Test programs	Fuel	Release/Release rate	No. of tests	Objectives	Surface emissive power (kW/m)	flame speed (m/s)
Maplin Sands Shell, 1980	LNG	20-40 kg/s (cont.)	3	Flame propagation, thermal radiation, overpressure	137-225	4.5-6.0
		3500-5000 kg (inst.)	2			
	LPG	20-55 kg/s (cont)	3			
		4500 kg (inst.)	1			
Coyote, China Lake LLNL, 1981	LNG	100-120 Kg/s (up to 12000 kg)	4	Flame propagation and thermal radiation	150-340	30-50
	Liquefied methane	100 kg/s (up to 11000 kg)	1			
Musselbanks, Terneuzen TNO, 1983	LPG	1000-4000Kg	7	Flame propagation and overpressure with / without obstacles	-	10.0-32.0

Rather few mathematical models have been proposed for flash fires as compared to other types of fire. In this section the most common models are analysed and commented.

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.

Among the empirical models implicitly based on this assumption is the one proposed by Einsenberg et al. (1975). It assumes that the cloud shape is a half ellipsoid. The estimation of the thermal radiation is based on the Stefan-Boltzman equation; this is a problem, as temperature is difficult to estimate due to its large variation (Lees, 2005). According to Einsenberg, the initial temperature of the flame is equal to the adiabatic flame temperature.

The calculation of the heat flux is a complex function of many factors. For example, it is difficult to estimate the emissive power and the time interval over which it can be applied, due to the short duration of the fire as well as its highly transient nature. The model estimates the volume and area of radiation and an effective duration of the flash fire; therefore, it assumes 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 presented by the authors were validated by experiments with up to 200 cm³ of various substances (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. In this respect, there is general agreement on the conclusions from field experiments, that a flash fire does not become a fireball except from the unusual situation that would arise from a massive release of fuel gas or liquid/gas together with an ignition advance. In addition, tests conducted by Shell with LNG and LPG, as well as previous tests involving LNG vapor clouds, do not confirm Fay and Lewis proposition.

Raj & Emmons (1975)

One of the most widely used and cited model has its origin in another one previously developed by Stewart (Raj and Emmons, 1975) for pool fires. It is based on the following assumptions (Mudan and Croce, 1988):

- The geometry of the fuel vapor cloud is two dimensional.
- The combustion is controlled by natural convection.
- The flame propagation velocity with respect to the unburned gases is constant.
- The depth of the vapor cloud is uniform and unaffected by the flame.
- The variation of the depth of the vapor cloud in the preburning region is linear.
- The steady state turbulent flame correlation between the visible flame height and width of the base is valid.

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, 1994). These results in an approximate semiempirical expression:

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

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. It assumes that this height at a given position is related to the mass of flammable material in the cloud at that point. These authors note that the flame speed for a flash fire is presumably a function of the laminar flame velocity and the actual temperature of the gas. The model proposed by Cracknell and Carsley 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.

To calculate the height of the flame, the mass of fuel in the cloud above a unit surface area, M_{area} , is first estimated from a dispersion model, and based on the first assumption of these authors, the flame height H is given by:

$$H = V_{prods} \times M_{area} \quad (2)$$

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 that generated by obstacles, on flame speed. The flow in a flash fire is turbulent, as shown by the experiments with propane which give average speeds around 12 m/s (Mizner and Eyre, 1982), and it has also been observed in experiments that the speed at combustion in premixed flame is faster at the edges.

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 numerical model incorporates the variables of wind speed, temperature, density and different atmospheric stability classes. The model results were compared with analytical model results quoted in CCPS. From these results it was observed that the values of the maximum flame height predicted by CCPS were much higher than the maximum flame height predicted by the numerical model of CCPS in similar conditions. This model assumes:

- A two dimensional geometry.
- The combustion of the flammable cloud is controlled by natural convection.
- The depth of the vapor cloud is small compared with the height of the flame.
- The depth of the vapor cloud is uniform and unaffected by the fire, creating a flow of vapor and air in the region of the cloud.
- The width of the fuel supply and fuel release rate constant.
- The fuel is continuously released from the fuel source.

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 an idealized situation, in which a planar flame front spreads horizontally through a uniform vapor of finite depth and fixed molar concentration on the ground.

CONCLUSIONS

The historical survey has shown that most flash fires occurred in process plants (36%), followed by transportation, storage and transfer. The main cause of flash fires was mechanical failure (44%), being the most common failure that originated by overpressure. LPG (liquefied petroleum gas) was the substance most frequently involved in accidents (42%). The most frequent scenario (64% of cases) was an initial release of flammable material originating a vapor cloud that subsequently ignited. In 33% of accidents there was an escalation of consequences after the flash fire. The most frequent sequence (24% of cases) was a flash fire followed by a series of explosion/fire.

Few large scale experimental studies have been performed on flash fires. Furthermore, there are few models, the most widely used being the one developed by Raj and Emmons. However, all these models have significant limitations and areas of uncertainty.

Flash fires are still poorly known, as compared to others types of fires, being this partly due to the difficulty found in experimental work. Therefore, research is necessary in areas such as:

- the shape and size of flame
- the estimation of view factors and emissive power of the flame

- the dependence of the velocity of propagation of the flame with respect to the composition of the cloud, wind speed and ground roughness.

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