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Study on ignition probability of flammable materials after leakage accidents

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Abstract

It is a key step of quantitative risk analysis (QRA) to estimate ignition probability of flammable materials after leakage accidents. This paper reviews the available literature and expert opinion on how to evaluate and determine ignition probability value, and it was detailedly discussed on the main influencing factors of ignition probability, including flammable material properties, mass flow rate of flammable materials spillage, ignition resources and ignition controls. Moreover, the operational and practical ignition probability value could be estimated from the all way of classifications of flammable material, mass flow rate, ignition resources, hazardous areas and ignition prevention and control measure. Furthermore, the more practical ignition probability model was put forward that the ignition probability was the maximum value of the probability decided by material properties (P_{MP}), mass flow rate(P_Q) and ignition resources(P_{IS}) with the factor of preventing and controlling ignition (K_{IC}). Finally, the further research was proposed to assign some feasible weigh factors of the ignition probability for flammable materials after leakage accidents.

Keywords: ignition probability; flammable material; leakage accident; QRA

1. Introduction

Ignition probability refers to the ignited probability of some flammable materials after leakage. Estimation of ignition probability is a key step in the quantitative risk analysis (QRA) for installations where flammable liquids and gases are stored or transported [1–2]. Ignition can be separated into the immediate ignition and delayed ignition. Immediate ignition can be considered as the situation where the flammable materials are ignited immediately after leakage accidents by auto-ignition or accident ignition source. Delayed ignition is the result that the release and diffusing flammable gas cloud is ignited by other ignition sources apart from the release point. It is assumed to result in flash fires or explosions, and also to burn back to the source of the leak resulting in a jet fire or a pool fire. None of the existing accident databases makes a clear distinction between delayed and immediate ignition [3]. Sometime they can be distinguished in principle, but it is not always in practice. So, in this paper, ignition probability data includes both immediate and delayed ignition probability without some declaration. At present, QRA for accident consequences puts much emphasis on the influencing radius of accident, and some research on the determination of ignition probability value is ignored [4–5]. Therefore, it is necessary to comprehensively study on the influencing factors of determining the value of ignition probability and the ignition probability models according to some different scenarios.

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2. Influence factors of determination of ignition probability value

In the study by A Ronza et al (2007), a comprehensive collection of ignition probability data found in specialized risk assessment literature was listed. Nineteen studies were found that contained quantitative ignition probability data of flammable spills. According to these studies, the factors that influence ignition probability are: (1) flow rate or amount released: the greater the release, the larger the area covered by the ignitable cloud and the higher the probability of it finding an ignition source; (2) the substance released: the more volatile and flammable the material, the more likely the ignition; (3) the characteristics of the surroundings and the general conditions of the leak, on which the number and effectiveness of potential ignition sources depend. In some literatures [1–2, 6–7], delayed ignition probability is considered to be significantly affected by material released, cloud size, release duration and cloud location and number of available ignition sources. The following will focus on analysis and comparation with much scientific research on ignition probability models and expert opinion. Some view about these factors of determination of ignition probability will be put forward.

2.1. Flammable material properties (MP)

Some benchmarks on flammable material properties include flash point temperature (FPT), ignition temperature (IT),, auto-ignition temperature (AIT), minimum ignition energy (MIE), the lower flammable limit (LFL) and the upper flammable limit (UFL). Flammable material properties can be regarded to the function of these variables. Ignition will occur only if a gas or vapour cloud finds an ignition source within its flammable range (The concentrations between LFL and UFL constitute the flammable range). FPT is a key parameter in the hazard classification of flammable materials and in determining their likelihood of ignition. For example, a hydrocarbon fluid which has a flash point below ambient temperature when released to atmospheric pressure has the potential to be ignited. A kind of gas or vapour with low flash point can be readily ignited by a small flame or spark, whereas a kind of non-volatile liquid with high flash point would require a much more intensive heat source.

How the MP influences on the determination of ignition probability is discussed in *Purple book*, BEVI manual and some other literatures as following: According to Purple book [1], MP is a key factor to determine ignition probability. The probability of direct ignition for stationary installations is given in Table 1.

Table 1. Probability of direct ignition for stationary installations

Source		Substance		
Continuous/($kg \cdot s^{-1}$)	Instantaneous/kg	K1-liquid	Gas, low reactive	Gas, average/high reactive
<10	<1 000	0.065	0.02	0.2
10–100	1 000–10 000	0.065	0.04	0.5
>100	>10 000	0.065	0.09	0.7

In the study by Mike Moosemiller (2011), the probability of immediate ignition ($P_{\text{imm.ign}}$) depends upon both the potential for auto-ignition and the potential for static discharge. In this model, the former is related to the release temperature (T) relative to the auto-ignition temperature (AIT), and the latter to the minimum ignition energy (MIE) and “release energy” for the material being released. The “release energy” may be considered a function of the process pressure, or release rate, or some other surrogate parameter. These variables are taken into account, resulting in the following formula

$$P_{\text{imm.ign}} = P_{\text{former}} + P_{\text{latter}} = [1 - 5000e^{-9.5(T/\text{AIT})}] + [0.0024 \times (145.04P)^{1/3} / (\text{MIE})^{2/3}] \quad (1)$$

where AIT and T are in degrees Fahrenheit, P is in MPa, and MIE is in mJ. The following constraints place on this equation. A minimum value of 0 is allowed for T. For T/AIT<0.9, P_{former}=0; For T/AIT>1.2, P_{former}=1. $P_{\text{imm.ign}}$ cannot be greater than 1.

A Ronza (2007) analyzed tens of thousands of records of hydrocarbon spills by HMIRS (a database about hazardous materials incident reporting system). The relationship between the statistical data of ignition probability and the average flash temperature of the hydrocarbon spilled is established. Fig.1 describes how ignition probabilities vary as the average flash point of the hydrocarbon blend. Furthermore, it is seen that the average ignition probability decreases with the flash temperature of the hydrocarbon spilled.

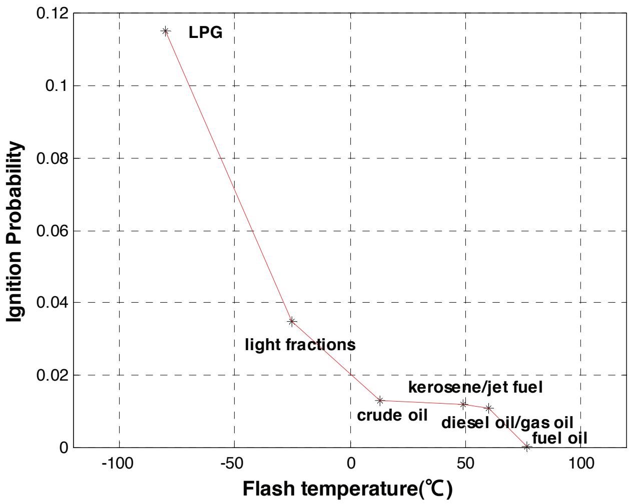

Fig. 1. Relationship between the average HMIRS ignition probability data and the average flash temperature of the hydrocarbon spilled.

BEVI manual [2] provides a more scientific method of determining ignition probabilities, which gives the different values according to the categories of some flammable materials. The definition of the substance category is given in Table 2, which derived from WMS (environmentally hazardous substances act).

Table 2. Classification of flammable substances

Substance category	WMS category	Limits
Category 0	Extremely flammable	Liquid substances and preparations with a flash point lower than 0 and a boiling point (or the start of a boiling range) less than or equal to 35 °C; Gaseous substances and preparations that may ignite at normal temperature and pressure when exposed to air
Category 1	Highly flammable	Liquid substances and preparations with a flash point below 21 °C, which are not, however, extremely flammable
Category 2	Flammable	Liquid substances and preparations with a flash point greater than or equal to 21 °C and less than or equal to 55 °C
Category 3		Liquid substances and preparations with a flash point greater than or equal to 55 °C and less than or equal to 100 °C
Category 4		Liquid substances and preparations with a flash point greater than 100 °C

The probability of direct ignition depends on the type of installation (stationary installation or transport unit), the substance category and the outflow quantity. For example, the values for stationary installations are given in Table 3.

Table 3. Probability of direct ignition for stationary installations

Substance category	Source term-continuous/(kg·s^{-1})	Source term-instantaneous/kg	Probability of direct ignition
Category 0 Average/high reactivity	<10	<1 000	0.2
	10–100	1 000–10 000	0.5
	>100	>10 000	0.7
Category 0 Low reactivity	<10	<1 000	0.02
	10–100	1 000–10 000	0.04
	>100	>10 000	0.09
Category 1	all flow rates	all quantities	0.065
Category 2	all flow rates	all quantities	0.01
Category 3, 4	all flow rates	all quantities	0

The essential factor of MP influencing the ignition probability is mainly inclusive FPT, AIT and MIE. Considering of some inherent positive correlations among the flammable properties, it is appropriate to choice the variable of FPT or MIE as the independent variable of the ignition probability function. For example, when we use the suggested formula (1) to calculate the ignition probability of some flammable materials, the formula can be simplified to the correlation of just about MIE because T/AIT is less than 0.9 in most cases. In order to balance the defect between expert opinion on ignition probability and statistical analysis of the existing accident database, it will have better objectivity and operability to determine the ignition probability of material according to the categories of some flammable materials, just like the BEVI Manual using the classification of substance to determine the value of ignition probability. At the same time, this method is a more preferable especially when the accident scenes are not detailed.

2.2. Mass flow rate of flammable materials leak (Q)

Amount spilled of flammable materials can be considered to the function of flow rate, the duration time of leak, the diameter of leakage location and the pressure difference between inner and outer. It tends to determine the value of ignition probability using the mass flow rate rather than other variables. Above a few tables several methods of determining the value of ignition probability are directly given through the amount spilled of flammable materials. In addition, Cox et al (1990) suggested a correlation for the probability of ignition based on mass flow rate, i.e. for continuous rather than instantaneous releases. It is assumed that the probability of ignition is proportional to a power of the mass flow rate, and the constant of proportionality and the power are then set from a few data points. If the mass flow rate is denoted by Q (kg/s), the probability of ignition for a particular scenario is approximately given by

$$p = aQ^b \tag{2}$$

where values of the coefficients a and b are estimated for a few scenarios. A Ronza (2007) used the similar methodology to analyze the correlations of ignition probability and the mass flow rate such as LPG, light fractions, crude oil kerosene, jet fuel diesel oil and gas oil. The coefficients a and b resulting from the fit curves are obtained respectively. *A guidance for quantitative risk assessment in the petrochemical plant* (2007, China Petrochemical Press) also advised the empirical formula of determining the value of delayed ignition probability as following [8]

$$P_{\text{gas.delay.ignition}} = (\mathrm{e}^{-4.16} m^{0.642}) \times (\mathrm{e}^{-2.995} m^{0.38}) \tag{3}$$

$$P_{\text{liquid.delay.ignition}} = (\mathrm{e}^{-4.333} m^{0.392}) \times (\mathrm{e}^{-2.995} m^{0.38}) \tag{4}$$

where m is the mass flow rate, kg/s.

A report (2010, The International Association of Oil and Gas Producers) illustrated a better method of determining the value of ignition probability, which calculated the value of ignition probability with different mass flow rates by means of using the end point value of four sections of broken lines[9–10]. The data used to generate the lines are shown in Table 4. This specifies the release rates (RR, kg/s) and ignition probabilities (P) relating to each of the points bounding the segments as indicated in Fig.2.

Table 4. Data for Look-up Correlations

Scenario type	Point 1		Point 2		Point 3		Point 4	
	RR/(kg·s^{-1})	P	RR/(kg·s^{-1})	P	RR/(kg·s^{-1})	P	RR/(kg·s^{-1})	P
Small plant gas LPG	0.1	0.001	1.00	0.002 5	3.00	0.01	498.99	0.60
Small plant liquid	0.1	0.001	1.00	0.002 4	100.00	0.10		
Large plant gas LPG	0.1	0.001	1.00	0.002 5	260.00	0.65		
Large plant liquid	0.1	0.001	1.00	0.002 5	109.99	0.13		
Large plant congested gas LPG	0.1	0.001	1.00	0.002 5	70.00	0.43	325.03	0.70
Tank gas LPG plant	0.1	0.001	1.00	0.001 2	102.84	1.00		
Tank gas LPG storage only industrial	0.1	0.001	1.00	0.001 2	100.00	0.23	988.11	1.00
Tank gas LPG storage only rural	0.1	0.001	1.00	0.001 2	10.00	0.02	52551	0.50
Offshore process liquid	0.1	0.001	100.00	0.02				
Offshore process gas typical	0.1	0.001	3.00	0.01	37.01	0.04		
Tank liquid-diesel and fuel oil	0.1	0.001	1.00	0.001	7.00	0.001 4	25.55	0.002 4

The logarithm of the required probability is obtained by the following formula

$$\lg P_{\text{ign}} = \lg P_{\text{ign.lower}} + \frac{(\lg Q - \lg Q_{\text{lower}})(\lg P_{\text{ign.upper}} - \lg P_{\text{ign.lower}})}{\lg Q_{\text{upper}} - \lg Q_{\text{lower}}} \tag{5}$$

where P_{ign} is the required ignition probability corresponding to release rate Q, $P_{\text{ign.lower}}$ is the ignition probability at a release rate of Q_{lower} (the lower bound of the relevant curve section) , and $P_{\text{ign.upper}}$ is the ignition probability at a release rate of Q_{upper} (the upper bound of the relevant curve section).

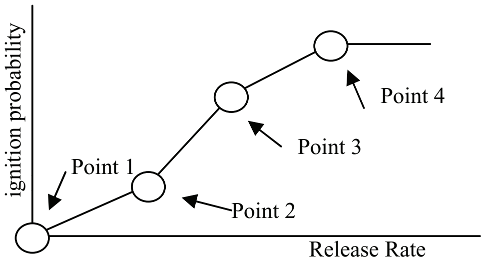

Fig. 2. Relationship of release rate (RR) and ignition probability (*P*)

It tends to determine the value of ignition probability using the flow rate rather than other variables. It is more scientific to determine the value by dividing into interval segments in according with the mass flow rate on some typical scenarios because the relatively accurate statistical value of these end points can guarantee the relatively correct result of different flow rate. The operability and objectivity will be explicit, and it is convenient to construct a spreadsheet or some program to carry this out.

2.3. Ignition sources (IS)

Ignition source is a key factor determining the value of ignition probability. Rew & Spencer (1997) gave a framework ranking system, derived from a number of some references, which was given in Table 5.

Table 5. Framework ranking system for ignition sources

Category (strength of source)	Examples of ignition sources	Ignition potential
Certain	Pilot light; open flare	$p=1$
Strong	Electric motors; hot work	$p>0.5$
Medium	Vehicles; faulty wiring	$0.5>p>0.05$
Weak	Electrical appliances; mechanical sparks	$p<0.05$
Negligible	Intrinsically safe equipment; radio frequency sources	$p=0$

In the study of Purple book, the probability of delayed ignition caused by an ignition source can be modeled as

$$P(t) = P_{\text{present}}(1 - \mathrm{e}^{-\omega t}) \tag{6}$$

where $P(t)$ is the probability of an ignition in the time interval 0 to t(-); P_{present} is the probability that the source is present when the cloud passes(-);ω is the ignition effectiveness, s^{-1}; t is time, s. The ignition effectiveness, ω, can be calculated given the probability of ignition for a certain time interval. Fig.3 shows the probability of ignition for a time interval of one minute for a number of sources.

In the study of Mike Moosemiller (2011), the similar theory was used to propose a calculation formula of the ignition sources influencing factor (M_{duration}), which is given below [11].

$$M_{\text{duration}} = 1 - (1 - s^2) \times \mathrm{e}^{-(0.015 \times s)t} \tag{7}$$

where strength “*s*” is denoted to be probability of ignition in one minute. The equation (7) takes a modified form of the equation (6).

Not only the ignition sources are taken into account, but also the size and duration time of the gas cloud that continuously covers the ignition source influence on the probability of ignition. Simmons (1974) conducted a survey of 59 incidents of ignition of clouds of LNG or LPG resulting from accidental spills due to transportation [12]. For these, the size of the cloud when ignition occurred was estimated and fitted the probability of ignition as a function of cloud area. By considering in depth, for a flammable cloud of area A, containing a random distribution of ignition sources with parameters λ, p and a, the probability $Q(t)$ of no ignition at time t in a given type of scenario is [6–7]:

$$Q(t) = \exp(-\mu A\{1-(1-ap)\mathrm{e}^{-\lambda pt}\}) \tag{8}$$

where μ is the average number of ignition sources per unit area; p is the ignition potential of a source (0–1); a is the rate of activation of the source; λ is the proportion of time that the source is active.

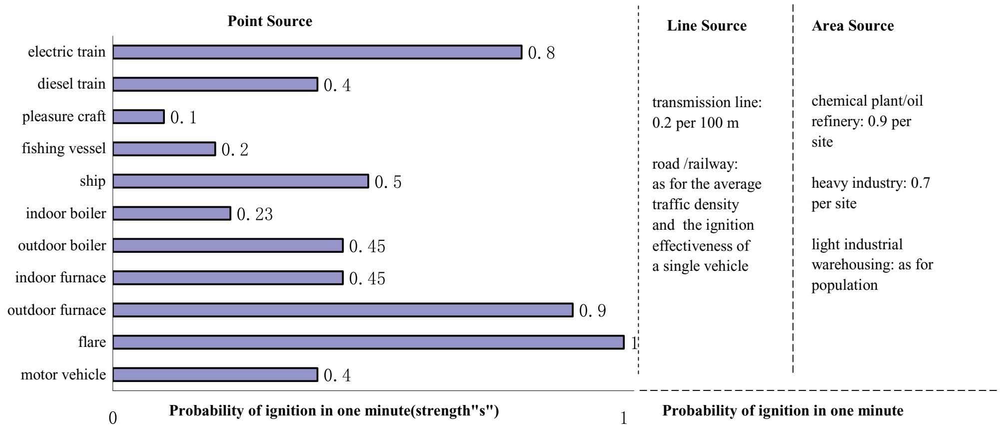

Fig. 3. Probability of ignition for a time interval of one minute for a number of sources.

The existing ignition resources and the contact with the gas cloud are the essential conditions resulting in ignition. The theory model (equation (8)) built is correct, but the calculation in practice is very difficulty because of the uncertain distribution and appearance of the ignition resources. So it is better ways to classify the ignition sources and use the recommended equations by some experts such as the equation (7). Due to the influence of ignition sources, semi-quantitative estimation of ignition probability is the preferable strategy to qualitative estimation and theoretical calculation.

2.4. Ignition controls (IC)

The key approaches to controlling ignition sources are: (1) Hazardous area classification, which essentially, defines the areas where flammable substances may occur and determines the controls over the ignition sources in design and normal processes in these areas. (2) Permit-to-work systems, which ensure that any non-routine work is carried out in a safe manner and determine the controls over the temporary and transient ignition sources. In most cases, it is often more appropriate to define the parameters for a "typical" level of ignition control and then to use the factors to determine other control levels accordingly. An estimation of ignition probability is to rank system of ignition source controls just as Table 6 [6].

Certainly, there are other measures to decrease the ignition probability such as the effectively ventilation, the essential safety design of some electrical equipments, the strict management system, etc.

3. Ignition probability modeling

Some main factors determining the value of ignition probability are discussed above. Equation (8) is the more suitable model in quantitative calculation. But the calculation is very difficulty in practice because of the uncertain distribution and appearance of the ignition resources. During the course of carrying out quantitative risk analyses, the model is lack of practicability. So the new model must be yielded to the practical availability. In view of the nonlinear relationship among the factors of MP, Q, IS and IC and these variables should be considered comprehensively in the new model, the more practical method is advised as following: P_{IP}=maximum(P_{MP}, P_Q, P_{IS})×K_{IC}, where P_{IP} is the ignition probability, P_{MP} is the probability decided by material properties, P_Q is the probability decided by mass flow rate, P_{IS} is the probability decided by ignition resources, and K_{IC} is the factor decided by the ignition controls.

Table 6. Framework ranking system of ignition source controls

Type	Probability of ignition, in presence of flammable substance		Ignition control
	Quantitative	Qualitative	
Ideal	0	None	Design and maintenance ensures no ignition source at any time
Excellent	0.1	Minimal	Well designed and maintained – ignition only arising from rare events (e.g. unforeseen failure of equipment)
Typical (good)	0.25	Limited	Designed to meet standards and maintained regularly—ignition eliminated in normal operation, but potential for failure of systems or changing circumstances to result in occasional ignition source
Poor	0.5	Poor	Does not meet precise standards and poorly maintained—significant potential for ignition sources to occur
None	>0.5	None	No adherence to standards and little maintenance—significant potential for ignition sources to occur

By the analysis of the influence factors or models of ignition probability, some suggestions are given as following: (1) For the P_{MP}, it is feasible and necessary to categorize the flammable materials referred by WMS and BEVI. (2) For P_Q, it is a good strategy to determine the value by dividing into interval segments in according with the mass flow rate on some typical scenarios, which is referred by mathematical functions drawn from some look-up correlations. (3) For P_{IS}, it can be calculated directly by equation (8) if the gas cloud area, duration time and the detail distribution of the existing ignition resources are known. But in most cases, the accidents scenarios are unknown. Therefore, it is better ways to classify the ignition sources and use the recommended equations by some experts such as equation (7). Semi-quantitative estimates of ignition sources are the preferable strategy to qualitative estimation and theoretical calculation. (4) For K_{IC}, it is also determined by classification of some control measures including management, electrical equipments, etc. K_{IC} is the modification parameter. (5) In order to make the more conservative result, the function of ignition probability is the maximum value of $(P_{MP}, P_Q, P_{IS})\times K_{IC}$ rather than the minimum.

4. Conclusions

(1) The main influence factors of ignition probability are inclusive of the flammable material properties, mass flow rate of flammable materials spillage, ignition resources and ignition controls. (2) Estimation of ignition probability is a key step in the quantitative risk analysis (QRA). Classifications of flammable material, the mass flow rate, ignition resources, hazardous areas and ignition controls measures are put forward, which makes the determination of ignition probability operational and practical. (3) The more practical ignition probability model is advised as following: P_{IP}=maximum $(P_{MP}, P_Q, P_{IS})\times K_{IC}$. (4) After classification of some factors, the assigned feasible weigh according to contribution to the ignition probability will be further researched, which brings convenience to construct the a few variables function model.

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