

Fire and Explosion Risk Analysis of Oxidation Process Based on FFTA-LOPA Method

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Abstract. In order to improve the safety of the chemical process, a method combining the fuzzy fault tree analysis (FFTA), the layer of protection analysis (LOPA) and the risk matrix was proposed. Taking the oxidation process as an example, the risk of the ethylene oxide synthesis process was analyzed. Fire and explosion accidents were used as accident consequence scenes to analyze the fault tree. After calculating the fuzzy probability of the top event, the risk level was obtained according to the risk matrix. The result was shown that the risk level was fallen to acceptable level after adding independent protection layers. This method provided a new research direction for risk analysis of chemical process.

1. Introduction

With the continuous development of the economy, the number of chemical industries has increased, and the dangerous processes involved in chemical production have also become more and more. Therefore, the terrible accidents will be brought out once the safety of the process is ignored. The raw materials, oxidants and products involved in the oxidation process generally have characteristics of flammable and explosive. In case of high temperature, friction, impact and so on, it is easy to cause fire and explosion accidents, resulting in considerable economic losses and personnel casualties.

The research of chemical process risk has become the direction of many scholars at home and abroad. The risk analysis of HAZOP has been widely used in the petrochemical enterprises [1][2][3]. Wang Q Q [4] analyzed the risk of fire and explosion accidents in heavy oil catalytic process based on BN-LOPA method. Fault Tree Analysis (FTA) is also a quantitative method widely used in risk analysis. However, traditional fault tree has certain limitations. In the actual production process, the probability of occurrence of basic events cannot be an exact value [5]. Therefore, the fuzzy fault tree analysis (FFTA), the layer of protection analysis (LOPA) and the risk matrix and was used to perform risk analysis in this paper. Fire and explosion accidents of the ethylene oxide synthesis were chosen as the accident scenes. The risk level was determined according to the probability of the accident and the severity of the accident.

2. FFTA-LOPA analysis method

2.1. FFTA theory



2.1.1. *Definition.* A L-R typed membership function is widely used in engineering, and its reference functions come in many forms, including triangle, normal and sharp type. Because the probability of production equipment failure did not occur to a certain range, a normal function was used in this paper. The membership function of \tilde{A} can be expressed in equation (1).

$$U_{\tilde{A}}(x) = \begin{cases} L[(m-x)/\alpha] = \exp\left[-\left(\frac{m-x}{\alpha}\right)^2\right]; & x \leq m, \alpha > 0 \\ R[(x-m)/\beta] = \exp\left[-\left(\frac{x-m}{\beta}\right)^2\right]; & x > m, \beta > 0 \end{cases} \quad (1)$$

In the formula, the membership function of the fuzzy number \tilde{A} is generally recorded as $U_{\tilde{A}}(x)$, where m is the mean value and α , β is the left and right distribution, respectively. The wider distribution α , β is, the more blurred \tilde{A} is.

2.1.2. *Algebraic algorithms for fuzzy numbers.* Assuming that there are two fuzzy numbers: $\tilde{P}_1 = (l_1, m_1, n_1)_{LR}$, $\tilde{P}_2 = (l_2, m_2, n_2)_{LR}$. And then the algebraic algorithms for fuzzy numbers can be expressed in equation (2)–equation (5).

$$\tilde{P}_1 + \tilde{P}_2 = (l_1, m_1, n_1)_{LR} + (l_2, m_2, n_2)_{LR} = (l_1 + l_2, m_1 + m_2, n_1 + n_2)_{LR} \quad (2)$$

$$\tilde{P}_1 - \tilde{P}_2 = (l_1, m_1, n_1)_{LR} - (l_2, m_2, n_2)_{LR} = (l_1 - l_2, m_1 - m_2, n_1 - n_2)_{LR} \quad (3)$$

$$\tilde{P}_1 \times \tilde{P}_2 = (l_1, m_1, n_1)_{LR} \times (l_2, m_2, n_2)_{LR} = (l_1 l_2, l_1 m_2 + l_2 m_1, l_1 n_2 + l_2 n_1)_{LR} \quad (4)$$

$$K \times \tilde{P}_1 = K \times (l_1, m_1, n_1)_{LR} = (Kl_1, Km_1, Kn_1)_{LR} \quad (K \in R) \quad (5)$$

2.1.3. *AND and OR gates of fuzzy fault tree.* In the fault tree, the upper and lower levels of events can be linked through logical AND and OR gates. After introducing the concept of fuzzy numbers, the fuzzy AND and OR gates and their operation formulas are obtained based on the fault tree, as shown in equation (6) and equation (7).

Fuzzy AND gates:

$$\tilde{P}_{AND} = AND(\tilde{P}_1, \tilde{P}_2, \dots, \tilde{P}_n) = \prod_{i=1}^n \tilde{P}_i = \tilde{P}_1 \times \tilde{P}_2 \times \dots \times \tilde{P}_n \quad (6)$$

Fuzzy OR gates:

$$\tilde{P}_{OR} = OR(\tilde{P}_1, \tilde{P}_2, \dots, \tilde{P}_n) = 1 - \prod_{i=1}^n (1 - \tilde{P}_i) = 1 - (1 - \tilde{P}_1)(1 - \tilde{P}_2) \dots (1 - \tilde{P}_n) \quad (7)$$

2.2. LOPA theory

Layer of Protection Analysis (LOPA) is a semi-quantitative risk assessment method commonly used in the petrochemical enterprise [6]. The reliability of existing protection measures can be quantitatively analyzed and the ability to eliminate or reduce risks can be determined. The LOPA method is generally based on accidents with serious consequences, and all possible causes of accidents are found as initial events. Then, each independent protective layer (IPL) in existing protection measures is identified. Therefore, the probability of occurrence of the accident can be calculated through determining the probability of failure on demand (PFD) of each IPL. Finally, the risk level is determined, and the probability of occurrence of the accident is reduced to an acceptable level by adding IPLs.

After identifying all IPLs, the probability of a single accident scenario can be expressed by the following formula:

$$P_i^C = P_i \times \prod_{j=1}^J PFD_{ij} = P_i \times PFD_1 \times PFD_2 \times PFD_{ij} \tag{8}$$

In the formula, P_i^C is the probability that the initial event i causes the accident C , P_i is the probability of the occurrence of initial event i , and PFD_{ij} is the failure probability of IPLs, J is the number of IPLs.

2.3. Risk matrix

The risk matrix is the integration of the probability of an accident (P) and the severity of an accident (S) [7]. According to the 5×7 matrix (see Figure1) applied by the Centre for Chemical Process Safety (CCPS) of American Institute of Chemical Engineers and related literature [8], the probability of accident scenes was divided into seven levels as shown in Table 1, and the severity of the accident was divided into five levels comprising very low, low, middle, high, and very high level. Finally, the risk level was divided into four levels including acceptable, tolerance of acceptable, tolerance of unacceptable, and unacceptable risk.

From this, the general steps based on the FFTA-LOPA-risk matrix analysis can be concluded. First, the fault tree of the major accident scene was drawn and the fuzzy probability of the accident was quantitatively determined. Then according to the level of probability of the accident and severity of the accident, the corresponding risk level was found through the 5×7 matrix. Finally, through the addition of safety measures, the fuzzy probability of the accident was calculated and the corresponding risk level was determined. The relationship between FFTA, LOPA, and risk matrix is shown in Figure 2.

Table 1. Level of the accident probability (P).

Level	Range
I (Ignorable)	10^{-8} – 10^{-6}
II (Impossible)	10^{-7} – 10^{-5}
III (Very low)	10^{-6} – 10^{-4}
IV (Low)	10^{-5} – 10^{-3}
V (Medium)	10^{-4} – 10^{-2}
VI (High)	10^{-3} – 10^{-1}
VII (Very high)	10^{-2} –1

v	I	II	II	III	III	IV	IV
IV	I	I	II	II	III	III	IV
III	I	I	I	II	II	II	III
II	I	I	I	I	II	II	II
I	I	I	I	I	I	II	II
Severity level	I	II	III	IV	V	VI	VII
	Probability level						

Figure 1. 5×7 risk matrix.

3. Example applications and analysis

3.1. Drawing an fault tree

Ethylene oxidation to ethylene oxide is one of the typical oxidation processes. Ethylene, oxygen and circulating gas enter into the oxidation reactor after preheating, and then ethylene oxide is obtained under the silver catalyst. The process temperature is usually controlled at 220–280°C, and the operating pressure is usually set at 1–3MPa. Ethylene is a flammable gas with an explosion limit of 2.9–79.9% in oxygen. The exothermic reaction in the reactor is violent. Therefore, if the operation is improper, it will be prone to fire and explosion when it comes to ignition sources. Through the above analysis and the related literatures, a fault tree of the fire and explosion accidents was drawn during ethylene oxide synthesis process, as shown in Figure 3.

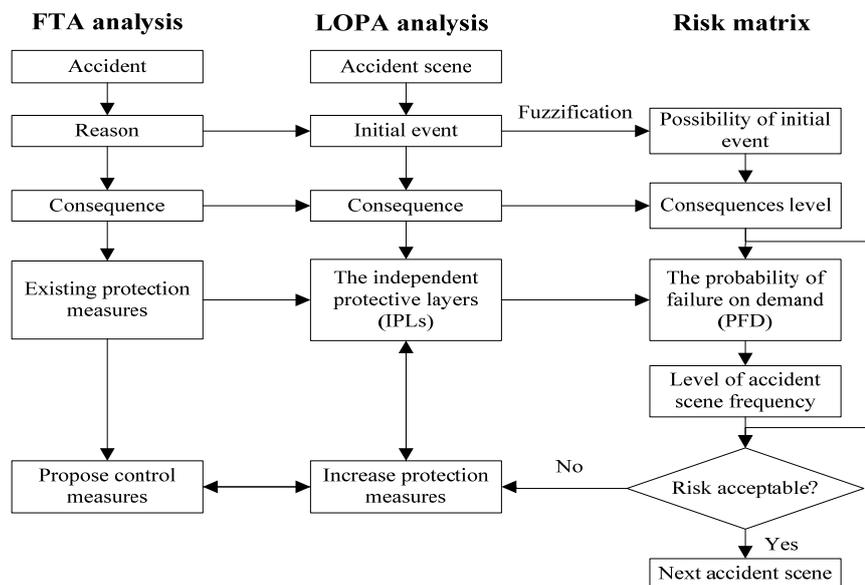


Figure 2. Relationship between FFTA, LOPA and Risk Matrix.

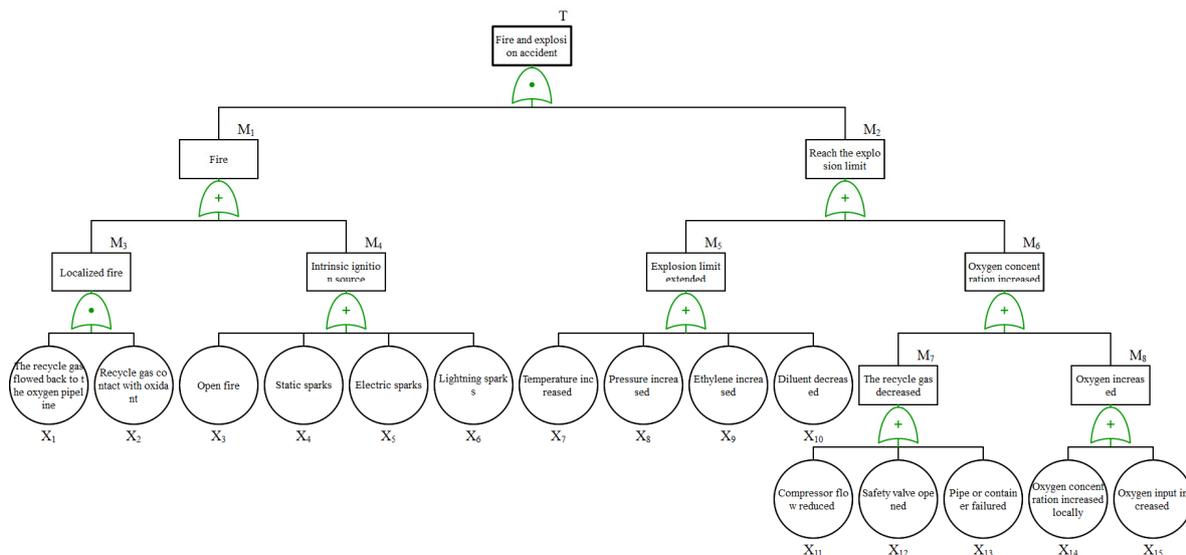


Figure 3. Fire and explosion fault tree.

$$\begin{aligned}
 T &= M_1 \bullet M_2 = (M_3 + M_4)(M_5 + M_6) \\
 &= (x_1x_2 + x_3 + x_4 + x_5 + x_6)(x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15}) \\
 &= x_1x_2x_7 + x_1x_2x_8 + x_1x_2x_9 + x_1x_2x_{10} + x_1x_2x_{11} + x_1x_2x_{12} + x_1x_2x_{13} + x_1x_2x_{14} + x_1x_2x_{15} \\
 &\quad + x_3x_7 + x_3x_8 + x_3x_9 + x_3x_{10} + x_3x_{11} + x_3x_{12} + x_3x_{13} + x_3x_{14} + x_3x_{15} + x_4x_7 + x_4x_8 + x_4x_9 \\
 &\quad + x_4x_{10} + x_4x_{11} + x_4x_{12} + x_4x_{13} + x_4x_{14} + x_4x_{15} + x_5x_7 + x_5x_8 + x_5x_9 + x_5x_{10} + x_5x_{11} + x_5x_{12} \\
 &\quad + x_5x_{13} + x_5x_{14} + x_5x_{15} + x_6x_7 + x_6x_8 + x_6x_9 + x_6x_{10} + x_6x_{11} + x_6x_{12} + x_6x_{13} + x_6x_{14} + x_6x_{15}
 \end{aligned}$$

According to the structure of the fault tree, the minimum cut sets of 45 were obtained. Similarly, the number of minimum path sets were obtained by transforming the fault tree into a success tree, including P_1 , P_2 , and P_3 .

$$\begin{aligned}
 P_1 &= \{x_1, x_3, x_4, x_5, x_6\} \\
 P_2 &= \{x_2, x_3, x_4, x_5, x_6\} \\
 P_3 &= \{x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}\}
 \end{aligned}$$

Because it was convenient to calculate the probability of the top event based on the minimum path set of the fault tree, the probability of the top event was $T = P_1P_2P_3$.

3.2. The fuzzy probability of the accident

From equation (1), it can be seen that the normal membership function is symmetric. If the degree of membership of x which is different from the average by 40% is 0.08, then there is the equation that $\alpha_i = \beta_i = 0.2517m_i$ [9]. Based on the relevant literatures and the experience evaluation of experts, the average m_i and the distribution α_i, β_i of the probability of occurrence of each basic event in the fault tree are listed in Table 2.

Table 2. The fuzzy probability and distribution of basic events.

Basic event	m_i	α_i, β_i	Basic event	m_i	α_i, β_i
x_1	0.05	0.012585	x_9	0.1	0.02517
x_2	0.05	0.012585	x_{10}	0.1	0.02517
x_3	0.2	0.05034	x_{11}	0.02	0.005034
x_4	0.1	0.02517	x_{12}	0.05	0.012585
x_5	0.05	0.012585	x_{13}	0.05	0.012585
x_6	0.05	0.012585	x_{14}	0.05	0.012585
x_7	0.05	0.012585	x_{15}	0.08	0.020136
x_8	0.1	0.02517			

According to the data in Table 2 and equation (7), the minimum fuzzy sets can be obtained as:

$$\begin{aligned}
 \tilde{P}_1 &= OR(\tilde{P}_{x_1}, \tilde{P}_{x_3}, \tilde{P}_{x_4}, \tilde{P}_{x_5}, \tilde{P}_{x_6}) = (0.3827, 0.08064, 0.08064) \\
 \tilde{P}_2 &= OR(\tilde{P}_{x_2}, \tilde{P}_{x_3}, \tilde{P}_{x_4}, \tilde{P}_{x_5}, \tilde{P}_{x_6}) = (0.3827, 0.08064, 0.08064) \\
 \tilde{P}_3 &= OR(\tilde{P}_{x_7}, \tilde{P}_{x_8}, \tilde{P}_{x_9}, \tilde{P}_{x_{10}}, \tilde{P}_{x_{11}}, \tilde{P}_{x_{12}}, \tilde{P}_{x_{13}}, \tilde{P}_{x_{14}}, \tilde{P}_{x_{15}}) = (0.4647, 0.08775, 0.08775)
 \end{aligned}$$

Therefore, the fuzzy probability of the top event was calculated by equation (6).

$$\tilde{P}_T = AND(\tilde{P}_1, \tilde{P}_2, \tilde{P}_3) = \tilde{P}_1 \tilde{P}_2 \tilde{P}_3 = (0.0681, 0.04154, 0.04154) = (0.02656 - 0.10964)$$

It was shown that the possibility of fire and explosion accidents in the synthesis of ethylene oxide was serious. Hence, a certain degree of protection measures should be set to reduce the risk. Through the application of the layer of protection analysis method [10] and consulting the related literatures, in the ethylene oxide synthesis process, the basic process control system can be used as the IPL₁ under normal conditions, and the PFD₁ was 0.1. When the process parameters were abnormal, the

personnel's operation intervention can be used as the IPL₂, and the PFD₂ was 0.1. When the process parameters were not controlled, the device and emergency response can be used as the IPL₃ to mitigate the consequences of the accident with the PFD₃ of 0.01.

Therefore, according to equation (8), it can be concluded that the fuzzy probability of the top event after adding IPLs was

$$\begin{aligned}\tilde{P} &= \tilde{P}_T \times PFD_1 \times PFD_2 \times PFD_3 = (0.0681, 0.04154, 0.04154) \times 0.1 \times 0.1 \times 0.01 \\ &= (6.81 \times 10^{-6}, 4.154 \times 10^{-6}, 4.154 \times 10^{-6}) = (2.656 \times 10^{-6} - 1.0964 \times 10^{-5})\end{aligned}$$

3.3. Risk analysis

According to the investigation report of the previous accident, fire and explosion accidents in the ethylene oxide synthesis process caused serious economic losses, casualties and social impacts. Therefore, the level of accident severity was V. Before the addition of protection measures, the fuzzy probability of the accident was (0.02656–0.10964), and its probability level was VII, the risk level was IV. After adding IPLs, the probability of the mitigating accident was (2.656×10⁻⁶–1.0964×10⁻⁵), its probability level was III. Then the risk level was reduced to II, which is tolerance of acceptable risk.

4. Conclusions

1. An FFTA-LOPA-risk matrix analysis method was established. The probability of the basic event in the fault tree was fuzzified. Combined with the LOPA method, the fuzzy probability of the occurrence of the top event after the addition of the independent protection layers (IPLs) was calculated. The risk matrix was used to classify risk levels. The rationality of this method was verified by the fire and explosion accidents in ethylene oxide synthesis process. The result was shown that the risk level of the accident was reduced from IV to II by adding IPLs, which is tolerance of acceptable risk.

2. Through the FFTA-LOPA-risk matrix analysis, it could not only analyze whether the existing safety measures can reduce the risk of the process, but also reduce the original high risk process to an acceptable level by adding the IPLs. This study provided a new research direction for the risk analysis of the chemical process.

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