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Study on risk assessment of chemical process based on an advanced layers of protection analysis method

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Abstract−This paper focuses on an advanced layers of protection analysis (LOPA) method to assess the risk of a chemical process. Based on the chemical accident statistics between 2001 and 2014 in China, an acceptable risk function was built for chemical processes to confirm the acceptable risk value for an accident scenario. The assessment index for an emergency system was developed to assess the protective function of emergency protection based on analytic hierarchy process (AHP), and the probability of failure on demand (PFD) of emergency protection was obtained by fuzzy comprehensive assessment method and fuzzy set theory. The proposed method was applied to a methanol distillation installation. The result showed that the protections, including emergency protection, were sufficient because the probability of mitigation protection (1×10^{-8}) was less than the acceptable risk value (3.04×10^{-7}). The advanced LOPA method was proven to be able to improve the integrity and accuracy of traditional LOPA.

Keywords: Layers of Protection Analysis, Emergency, Fuzzy Set, Risk Assessment, Chemical Process

INTRODUCTION

Risk assessment is one of the most important methods for ensuring the safety of chemical processes [1-3]. During production, in order to control the risk associated with chemical processes, multiple protective measures are usually adopted to keep the residual risk lower than the acceptable risk based on the inherent safety design. Therefore, it is important to assess the efficiency of these protective measures to guarantee the safety of chemical processes.

The concept of "protections" and the layers of protection analysis (LOPA) method were both developed by the Centre for Chemical Process Safety (CCPS). In a specific accident scenario, the initiating event frequency, consequence severity, and the probability of failure on demand (PFD) for all of the independent protections are used to evaluate the possibility of accidents [4].

The effectiveness of protective measures is then evaluated by comparing the mitigated risk with the acceptable risk. The LOPA method is more objective and easier to use compared with qualitative evaluation methods [5,6]. Thus, as a semi-quantitative risk assessment method, the LOPA method has become an important tool for risk analysis and evaluating chemical processes, as well as risk decision-making in recent years. To enhance its functions, LOPA is generally used with HAZOP, PHA, Bayes, Bow-tie, or other methods to assess the risk associated with a chemical process [7-11].

The acceptable risk is known to be a key factor in the LOPA method. The acceptable risk, which is the maximum allowable probability of the accident consequences for a selected scenario, provides guidance when making risk decisions. The acceptable risk can be characterized by casualties, economic losses, or environmental damage [12]. However, the determination of the acceptable risk is still uncertain during the safety process because it varies among countries due to political, economic, production, and other factors. In general, the F-N curve method, ALARP criterion, cost-benefit analysis, and historical accident data statistics are used to obtain acceptable risk criteria [13-15]. The accident data statistics method provides more objective and accurate results compared with the other three qualitative methods.

In addition, emergency protection is the last protective layer in a chemical process. The emergency system plays an important role in the risk control process and it can effectively prevent or control accidents [16]. However, it is difficult to determine the PFD of the protective layer in a quantitative manner due to the complex characteristics of an emergency. Therefore, the contribution of emergency protection to risk reduction in a chemical process is not included in the traditional LOPA. Obviously, ignoring the protective function of the emergency protective layer reduces the reliability of LOPA results. Thus, we propose an improved LOPA method, which considers the accident data statistics and emergency protection. The acceptable risk function is calculated based on an analysis of the accident statistics and the PFD of the emergency protection is determined by fuzzy comprehensive evaluation and using a trapezoidal fuzzy set method; thus, this advanced method is more accurate and comprehensive than the traditional method employed for chemical process risk assessments.

BASIC PRINCIPLES OF LOPA

In general, multi-layer protective measures are added to a chem-

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ical process to lower the risk. These protective measures are often called the protective layers or "protections" [4]. The safety function of these protections will greatly affect the safety integrity level of the chemical process.

Typical protections for a chemical process include the process design layer, basic process control system, process monitoring and artificial intervention layer, safety instruments system, mechanical protection layer, structure layer, and emergency system layer. As a semi-quantitative risk assessment method, LOPA typically uses order of magnitude categories that initiate the event frequency, consequence severity, and the likelihood of failure by independent protection layers (IPLs) to approximate the risk of a scenario. LOPA is usually applied based on a qualitative risk assessment (e.g., HAZOP) [17,18].

The probability of accident consequence C (such as a leakage, fire, or explosion) for the selected scenario is the product of the probability of occurrence for the initiating event and all of the independent protections for preventing the accident consequence. Thus, the probability of consequence C can be calculated according to Eq. (1).

$$f^c = f^i \times \prod_{j=1}^{j} PFD_j \tag{1}$$

where f^c the probability of accident consequence C is, f^i is the probability of occurrence for the initiating event, and PFD_j is the PFD of the j-th independent protection for preventing the accident consequence.

The probability of the accident scenario can be modified based on the probability of the focal consequence when further injury to a person due to the accident consequence is a concern. For example, people would be injured if they were exposed when an explosion occurred. The explosion could then cause an injury as a further accident consequence. The probability of a further accident consequence $f^{exp\ losion\text{-}injury}$ can be derived by adding the probability of exposure by a person during the accident P^{exp} and the probability of a person being injured P^s (some may not be injured) to Eq. (1), as shown by Eq. (2).

$$f^{exp\ losion\text{-}injury} = f^i \times \left(\prod_{j=1}^{j} PFD_{ij} \right) \times P^{exp} \times P^s \tag{2}$$

The risk of the chemical process will be considered unacceptable unless the probability of the accident consequence C is lower than the acceptable risk; otherwise, additional protections or measures should be considered to reduce the risk of the chemical process.

THE ACCEPTABLE RISK FUNCTION

For a selected scenario, LOPA requires a comparison of the probability of the accident consequence C with the acceptable risk to determine the adequacy of the protections. Generally, risk is the plus of the probability of the risk (p) and the consequence caused by the risk (c), shown as Eq. (3).

$$R = p \times c \tag{3}$$

The acceptable risk is a criterion value of the risk accepted by the public and usually expressed as a probability of an accident. It has been proved that the historical accident statistical analysis method is the best way to get the acceptable risk. Therefore, we propose an acceptable risk function for the chemical process to calculate the acceptable risk value, shown as Eq. (4), where the independent variable is the consequence C (loss of life) of accident and the dependent variable is the probability of accident.

$$f = T(C) \tag{4}$$

In China, accidents are classified into ordinary accidents, larger accidents, major accidents and disastrous accidents according to the accident's consequences, such as loss of life. In this study, we built the acceptable risk function for the chemical process based on the statistics and analysis of chemical accidents between 2001 and 2014. The statistical results of chemical accidents between 2001 and 2014 in China are shown in Fig. 1. To evaluate and manage the risk better, the consequence levels of accidents are divided into low, medium, large, major and disastrous levels in this paper. Among them, the accidents with large level are referred to as those accidents which will cause 3 to 10 people deaths.

Furthermore, the probability of accident consequence for a chemical enterprise can be obtained by the number of accidents divided into number of statistic years and number of chemical enterprises. For example, according to the accidents statistics in China, two "disastrous" accidents happened between 2001 and 2014, the number of statistic years is 14 and the number of chemical enterprises in China is two hundred and thirty-five thousand. Most of the

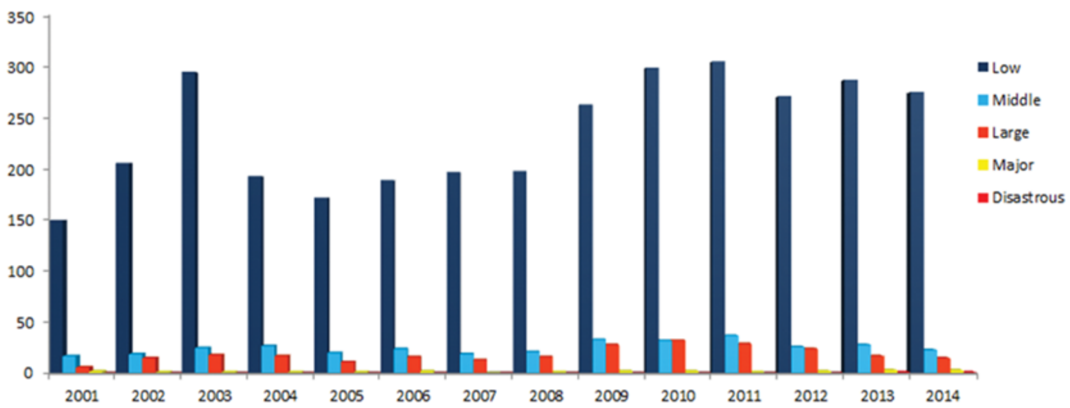

Fig. 1. Statistics of chemical accidents between 2001 and 2014 in China.

Table 1. Relationship between death number and accident probability

	Consequence level of accidents				
	Low	Middle	Large	Major	Disastrous
Number of deaths	$0<C_p\leq1$	$1<C_p\leq3$	$3<C_p\leq10$	$10<C_p\leq30$	$C_p>30$
f_p (/year)	1×10^{-3}	1×10^{-4}	3.99×10^{-5}	3.43×10^{-6}	3.04×10^{-7}

chemical processes are continuous in China. In viewing that the acceptable risk will be affected by many factors such as economy, politics and so on, we set an adjustment factor "k" to minimize the error. Here, the k value is set to 0.5. And then, the probability of the "disastrous" accident is 3.04×10^{-7}/year. Similarly, the probabilities for other level accidents can be obtained too. Therefore, the acceptable risk function for the chemical process can be built based on the statistics of chemical accidents, as well as the previous study and the standard classification for accident consequences in China, as shown in Table 1.

The probability in Table 1 is recommended to be the value of the acceptable risk, which can be confirmed when the death number is evaluated. The acceptable risk function can then be expressed as Eq. (5), where C_P is the number of deaths caused by an accident. There is a corresponding relationship between the number of deaths and the probability of the occurrence of a chemical accident. For example, if more than 30 people are killed in a chemical accident, the accident level is doomed as "disastrous" and the probability of the chemical accident with this consequence will be confirmed as 3.04×10^{-7}/year. And then, the LOPA can be carried out by comparing the probability of the accident consequence C with the acceptable risk.

However, there may be some deviations in the accident statistics due to some objective reasons. Therefore, there may be some differences in the risk probability and the actual value of the risk function.

$$f_P=T(C_P)=\begin{cases}1.0\times10^{-3} & (C_P\leq1)\\ 1.0\times10^{-4} & (1<C_P\leq3)\\ 3.99\times10^{-5} & (3<C_P\leq10)\\ 3.43\times10^{-6} & (10<C_P\leq30)\\ 3.04\times10^{-7} & (C_P>30)\end{cases} \quad (5)$$

Thus, in order to obtain the acceptable risk for an accident scenario, we combine the chemical acceptable risk function and accident consequence evaluation method. According to the mathematical model of the accident consequence assessment, the affected area and the number of deaths can be analyzed. Then, the acceptable risk value of a potential accident can be determined immediately according to Eq. (5).

QUANTIFICATION OF PFD FOR EMERGENCY PROTECTION

To quantify the protective function of emergency protection, we establish an evaluation index system for emergency protection based on the analytic hierarchy process (AHP) method, where the failure probability is obtained according to the fuzzy comprehensive assessment method and fuzzy set theory.

1. Assessment of Emergency Protection Function

According to the characteristics of the emergency protective layer, we build the evaluation index system for the emergency protection function and calculate the weight of each index based on the analytic hierarchy process (AHP) method, and the efficiency of the emergency protection is assessed by the fuzzy comprehensive evaluation method.

1-1. Evaluation Index System of Emergency Protection

It is emphasized that emergency protection is the last protective layer of the chemical process in the beginning of this paper. But it is difficult to quantify the efficiency of emergency protection because of its complexity. That is, the efficiency of emergency protection may be affected by many factors, such as the emergency equipment, emergency personnel, and emergency response. Appropriate and adequate emergency equipment is necessary to eliminate or prevent accidents; typical emergency equipment includes communication equipment, fire-fighting equipment, reconnaissance equipment and rescue equipment. During the emergency, the emergency personnel are the executor and controller of the accident emergency; the knowledge and skills about chemical accidents and emergency mastered by the emergency personnel will have an effect on the emergency strategies and actions. So, the emergency personnel need to master professional and comprehensive emergency knowledge and techniques. The emergency responses will determine the efficiency and result of the emergency. The emergency responses include emergency organization, emergency plan, emergency command and emergency rescue. So, an emergency is a complex multi-factor problem.

AHP is simple and effective for making analyses and comprehensive evaluation of complicated and indefinite problems that have multiple criteria and multiple factors [19,20]. This method is especially applied in those questions which are difficult to quantitatively analyze. AHP focuses on comparison between two indexes, and the processes of analysis and calculation are easily understood. The main steps of AHP include constructing a hierarchy structure model, establishing a judgment matrix, calculating the weight value and the consistency check and fuzzy evaluation. The result of AHP can be applied to make a fuzzy comprehensive evaluation.

In view of the complexity and multi-factor of the emergency protection, we can use the AHP method to establish the hierarchy structure model and judging matrix of the emergency protection, and to calculate the weight of each index quantitatively. And then, the evaluation result of the emergency protection can be obtained by the fuzzy comprehensive assessment. Shown as Fig. 2, the emergency protection evaluation index system was built according to the emergency equipment, emergency personnel, and emergency

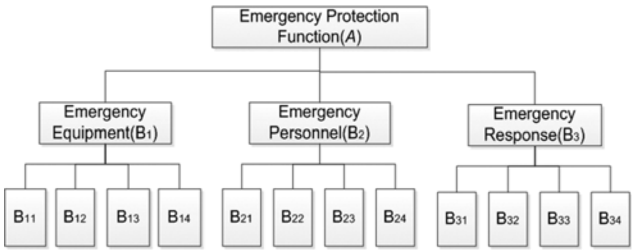

Fig. 2. Index system of emergency protection evaluation based on AHP.

response based on AHP method.

1-2. Calculation of Index Weight

Fig. 2 shows that the index system of emergency protection is a multi-level and multi-index system. There are three indexes in the second-level and sixteen indexes in the third-level.

The top level is emergency protection function (A) and the second level includes three indexes: emergency equipment (B_1), emergency personnel (B_2) and emergency response (B_3). Each second-level index includes many third-level indexes. Among of them, four items--communication equipment (B_{11}), fire-fighting equipment (B_{12}), reconnaissance equipment (B_{13}) and rescue equipment (B_{14})--are included in the emergency equipment (B_1). Emergency knowledge (B_{21}), emergency operations (B_{22}), emergency resilience (B_{23}), emergency techniques (B_{24}) are included in the emergency personnel (B_2). Emergency organism (B_{31}), emergency plan (B_{32}), emergency command (B_{33}) and emergency rescue (B_{34}) construct the emergency response (B_3). All the sixteen items will determine the efficiency of the emergency protection.

Judgment matrixes based on pairwise comparison among the indexes and their reciprocals can be built according to Fig. 2. The normalized feature vector of the maximum eigenvalues can be calculated to determine the weight of each index. The weight values of each index are listed in Table 2.

1-3. Building of Factor Set and Decision Set

According to the Fig. 2, the factor sets $U=\{u_1, u_2, \ldots, u_n\}$ are built as follows.

$A=\{B_1, B_2, B_3\}$
$B_1=\{B_{11}, B_{12}, B_{13}, B_{14}\}$
$B_2=\{B_{21}, B_{22}, B_{23}, B_{24}\}$
$B_3=\{B_{31}, B_{32}, B_{33}, B_{34}\}$
$B_4=\{B_{41}, B_{42}, B_{43}, B_{44}\}$

The decision set of emergency has seven levels $V=\{V_1, V_2, V_3, V_4, V_5, V_6, V_7\}$. The value of each level is shown in Table 3.

1-4. Fuzzy Comprehensive Evaluation

There is a fuzzy mapping from U to V, where $u_i \rightarrow f(u_i)=(r_{i1}, r_{i2}, \ldots, r_m) \in F(V)$. Then the fuzzy mapping f can identify a fuzzy relationship of U and V, here $R_f(u_i, v_i)=f(u_i)(v_i)=r_{ij}$; therefore, R_f can be represented by a fuzzy matrix as Eq. (6).

$$R=\begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{vmatrix} \tag{6}$$

Thus, a comprehensive evaluation can be performed and the efficiency of the emergency protection can be confirmed.

Table 2. Weight of each index of emergency protection

Judgment matrix	Weight value of index			
A	0.2648	0.1172	0.6144	
B_1	0.1408	0.5781	0.1263	0.1548
B_2	0.2017	0.3769	0.1624	0.2590
B_3	0.1620	0.2739	0.3780	0.1861

Table 3. Benchmark values for evaluation

No.	Evaluation standard	Efficiency level of emergency protection
1	[90,100]	Very high
2	[80,90]	Higher
3	[70,80]	High
4	[60,70]	Middle
5	[50,60]	Lower
6	[40,50]	Low
7	[0,40]	Very low

2. Method of Calculating PFD of Emergency Protection

It is still not possible to quantify the evaluation set for emergency protection efficiency, which includes high, higher, medium, lower, etc. Therefore, fuzzy set theory is used to replace the fuzzy language and to calculate the fuzzy probability.

2-1. Fuzzy Set Theory

The assessment results of the emergency protection are fuzzy linguistic values, such as higher, middle, lower and so on. It is obvious that these fuzzy results cannot reflect the efficiency quantitatively. Therefore, fuzzy set theory [21] is applied to calculate the fuzzy probability of failure on demand (PFD) of the emergency protection to complete the calculation of LOPA. In this paper the assessment results are turned into the corresponding trapezoidal fuzzy numbers with the converted function.

The trapezoidal fuzzy numbers and membership functions are given in Fig. 3. The fuzzy linguistic values are VL (very low), L (low), FL (lower), M (middle), FH (higher), H (high) and VH (very high). The membership function of each linguistic value can be obtained according to Fig. 3. For example, the membership function of "H" is given as Eq. (7).

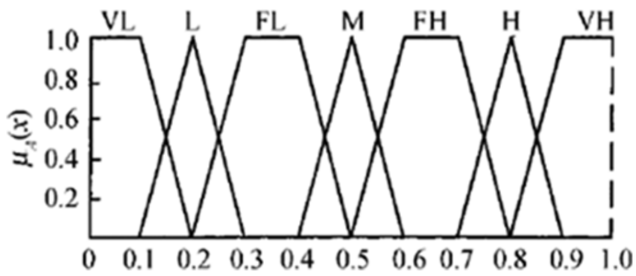

Fig. 3. Trapezoidal fuzzy numbers of linguistic values.

$$f_H=\begin{cases}\dfrac{x-0.7}{0.1} & (0.7\le x\le 0.8)\\ 0 & \text{other}\\ \dfrac{0.9-x}{0.1} & (0.8<x\le 0.9)\end{cases} \tag{7}$$

And then, the total fuzzy set and relation function can be determined by the "α" cut set and a fuzzy comprehensive treatment of all the fuzzy set. The "α" cut set of the "H" fuzzy set is shown as Eq. (8), and the relation function for fuzzy number W (z) can be expressed as Eq. (9).

$$W_\alpha=[0.1\alpha+0.7,\ 0.9-0.1\alpha] \tag{8}$$

$$f_W(z)=\begin{cases}\dfrac{z-a}{0.1} & (a\le z<a+0.1)\\ 1 & (a+0.1\le z\le b-0.1)\\ \dfrac{b-z}{0.1} & (b-0.1\le z\le b)\\ 0 & \text{other}\end{cases} \tag{9}$$

where "a" is the lower bound of the fuzzy number in the natural language, and "b" is the upper bound.

2-2. PFD of Emergency Protection

To compare the risk probability, the fuzzy number of the expert judgment needs to be transformed into the corresponding fuzzy possibility score (FPS). The minimum fuzzy set and the maximum fuzzy set are given by Eq. (10) and Eq. (11).

$$\mu_{min}(x)=\begin{cases}(1-x) & (0<x<1)\\ 0 & (\text{other})\end{cases} \tag{10}$$

$$\mu_{max}(x)=\begin{cases}x & (0<x<1)\\ 0 & (\text{other})\end{cases} \tag{11}$$

Next, the fuzzy probability of a fuzzy number can be obtained by Eq. (12). F_{PL} and F_{PR} are the left and right fuzzy values. F_{PL} is the maximum intersection points of the relation function for fuzzy number W (z) and the fuzzy maximum set $\mu_{max}(x)$; F_{PR} is the maximum intersection points of the relation function for fuzzy number W (z) and the fuzzy minimum set $\mu_{min}(x)$.

$$FPS=[F_{PR}+1-F_{PL}]/2 \tag{12}$$

Finally, to ensure consistency between the real and fuzzy probabilities of all events, it is necessary to transform the FPS into the fuzzy failure rate (FFR) according to Eq. (13) and Eq. (14).

$$FFR=\begin{cases}1/10^k & FPS\ne 0\\ 0 & FPS=0\end{cases} \tag{13}$$

$$K=2.301\times\left|\frac{1-FPS}{FPS}\right|^{1/3} \tag{14}$$

A CASE STUDY

The proposed method was applied to the risk assessment for a pressurized methanol distillation column. According to the HAZOP results, the initiating event was the failure of the pump and the consequence was the boiling liquid expanding vapor explosion (BLEVE) of the methanol distillation column. The volume of column was 132 m^3, the operating temperature was 130.3 °C and the operating pressure was 0.682 MPa.

Fig. 4. Death area of the explosion by CASSTQRA.

Based on the software quantitative risk assessment developed by China Academy of Safety Science and Technology (CASSTQRA), the explosion consequence of the pressurized methanol distillation installation was calculated and showed as Fig. 4. The death area of the explosion was surrounded by the red line, and the death radius of the explosion was 81.63 m, the released amount of methanol was 6,252 kg. According to the principle of maximum risk, it was supposed that all the employees in the death area would be killed by the accident. Therefore, there were 62 employees in the plant area who would be killed by the explosion, unfortunately, in this case. Because the value of C_p was bigger than 30, the level of the consequences was "Disastrous" and the acceptable risk was 3.04×10^{-7}/year according to Table 1.

Next, five experts groups, including safety, chemical engineering, fire, emergency, and management, were selected to build indexes judgments matrixes to calculate the weight of each index and the score of the fuzzy comprehensive evaluation. Finally, the efficiency level of the emergency protection can be determined.

Here, we selected one of the expert groups to show the calculating process. According to fuzzy judgments of the expert group, the fuzzy matrix of B_1 can be expressed as follows.

$$R(B_1)=\begin{pmatrix}0.3 & 0.3 & 0.2 & 0.1 & 0.1 & 0 & 0\\ 0.2 & 0.5 & 0.2 & 0 & 0.1 & 0 & 0\\ 0.4 & 0.3 & 0.2 & 0 & 0 & 0.1 & 0\\ 0 & 0.5 & 0.2 & 0.2 & 0.1 & 0 & 0\end{pmatrix}$$

Because the weight values of each index were calculated using the AHP method and listed in Table 2. W_{B1}=(0.1408, 0.5781, 0.1263, 0.1548). Therefore, the fuzzy comprehensive weight of B_1 was shown as follows.

$$R_{B1}=w_{B1}\bullet R(B_1)=\begin{pmatrix}0.1408\\ 0.5781\\ 0.1263\\ 0.1548\end{pmatrix}^T\bullet$$

$$\begin{pmatrix} 0.3 & 0.3 & 0.2 & 0.1 & 0.1 & 0 & 0 \\ 0.2 & 0.5 & 0.2 & 0 & 0.1 & 0 & 0 \\ 0.4 & 0.3 & 0.2 & 0 & 0 & 0.1 & 0 \\ 0 & 0.5 & 0.2 & 0.2 & 0.1 & 0 & 0 \end{pmatrix}$$

$$R_{B1}=(0.2084 \quad 0.4466 \quad 0.2155 \quad 0.0296 \quad 0.0873 \quad 0.126 \quad 0)$$

Also, we can achieve the fuzzy comprehensive weights of B_2 and B_3. So, the fuzzy comprehensive evaluation matrix of A was shown as follows.

$$R(A)=\begin{pmatrix} 0.2084 & 0.4466 & 0.2155 & 0.0296 & 0.0873 & 0.126 & 0 \\ 0.2009 & 0.4272 & 0.2259 & 0.0461 & 0.0837 & 0.0162 & 0 \\ 0.2546 & 0.3920 & 0.2186 & 0.0348 & 0.0622 & 0.0378 & 0 \end{pmatrix}$$

$$R_A=w_A \bullet R(A)=\begin{pmatrix} 0.2648 \\ 0.1172 \\ 0.6144 \end{pmatrix}^T \bullet$$

$$\begin{pmatrix} 0.2084 & 0.4466 & 0.2155 & 0.0296 & 0.0873 & 0.126 & 0 \\ 0.2009 & 0.4272 & 0.2259 & 0.0461 & 0.0837 & 0.0162 & 0 \\ 0.2546 & 0.3920 & 0.2186 & 0.0348 & 0.0622 & 0.0378 & 0 \end{pmatrix}$$

$$=(0.2351 \quad 0.4092 \quad 0.2178 \quad 0.0346 \quad 0.0712 \quad 0.0285 \quad 0)$$

Then the efficiency of emergency protection can be determined by the product of $R_A \cdot (95,85,75,65,55,45,35)^T$, and the evaluation result was 80.91. Therefore, according to decision standard values listed in Table 3, the fuzzy comprehensive evaluation level of the emergency protection was "higher."

Similarly, the fuzzy comprehensive evaluation results of other four expert groups were obtained; they were very high, high, medium, and high. According to the trapezoidal fuzzy numbers and membership functions (as shown in Fig. 3), the fuzzy linguistic values VH (very high), H (high), M (medium), FH (higher) and H (high) were translated into corresponding trapezoidal fuzzy numbers. The total fuzzy set under all the "α" cut set and fuzzy comprehensive evaluation was calculated by $W=f_{VH\oplus H\oplus M\oplus FH\oplus H}(x)=[0.1\alpha+0.62, 0.84-0.08\alpha]$. After the comprehensive treatment, the relationship function for the total fuzzy number W was shown as the following equation:

$$f_W(x)=\begin{cases} \dfrac{x-0.62}{0.1} & (0.62\le x<0.72) \\ 1 & (0.72\le x\le 0.76) \\ \dfrac{0.84-x}{0.08} & (0.76\le x\le 0.84) \\ 0 & (\text{other}) \end{cases} \tag{15}$$

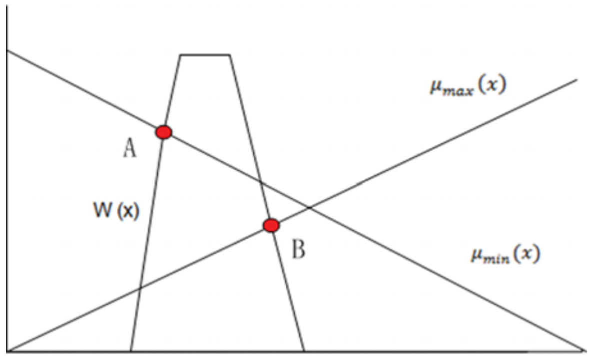

Fig. 5. Trapezoidal fuzzy numbers of linguistic values.

Then, according to Eq. (10), Eq. (11) and Eq. (12), we could calculate the left fuzzy value F_{AL} and the right fuzzy value F_{AR}; they were the maximum intersection points of the relation function for fuzzy number W (x) with the fuzzy maximum set μ_{max}(c) and fuzzy minimum set μ_{min}(c). The relationship of W (x) and maximum and minimum set is shown in Fig. 5.

Seen from Fig. 5, point A was the value of F_{PL}=0.6545, point B was the value of F_{PR}=0.7777. And then, according to Eq. (12) and Eq. (13), FPS=0.5616, K=2, and FFR=$1/10^k$=0.01. So, the fuzzy failure probability for the emergency protective layer was 1×10^{-2}. All of the independent protections and their PFDs are listed in Table 4. Here, the probability of exposure for a person and the occurrence of injury were both supposed to be 1.0.

Therefore, the value of the probability of the scenario in this case was 1×10^{-8}/year, which is less than the maximum allowable probability (3.04×10^{-7}/year). Obviously, the risk of the scenario was acceptable.

In the traditional LOPA, the safety function of the emergency protective layer was not considered, and the probability of the above scenario in the case was 1×10^{-6}/year, which was more than the maximum allowable probability, so the risk would not be accepted in the process. Thus, unnecessary protections would be added in the chemical process to satisfy the safety required. That will not only increase the cost burden of the enterprise, but also lower the focus of the key protections. This demonstrates that the emergency protective layer can be effective in reducing the risk of a chemical process, and the advanced method is more accurate and comprehensive.

CONCLUSIONS

An advanced LOPA method is proposed that considers the ac-

Table 4. Assessment records of the LOPA

1	2	3	4	5	6	7	8	9
Initiating event	Consequence severity	Consequence level	Acceptable risk	BPCS	Process monitor	SIS	Relief valve	Emergency
Pump failure 1×10^{-1}/year	Overpressure explosion 62 person died	Disastrous	3.04×10^{-7} /year	PFD 1×10^{-1} /year	PFD 1×10^{-1} /year	PFD 1×10^{-2} /year	PFD 1×10^{-1} /year	PFD 1×10^{-2} /year

ceptable risk and emergency protection when assessing the risk of a chemical process. This advanced method improves the traditional LOPA method by determining the acceptable risk of accident consequences for a selected scenario and by calculating the PFD for the emergency protective layer.

The acceptable risk function was established based on the statistical analysis of historical chemical accidents, which provides more objective and accurate results than other qualitative methods. Thus, the acceptable risk of an accident scenario can be calculated by combining the acceptable risk function with the accident consequence evaluation method. The acceptable risk of an accident consequence can then be determined immediately according to the acceptable function.

The PFD of the emergency protection was calculated according to a fuzzy comprehensive evaluation and a trapezoidal fuzzy number method. The protective efficiency of the emergency protection was evaluated by fuzzy comprehensive evaluation. Fuzzy set theory was used to replace the fuzzy evaluation language and to transform the FPS into the FFR. The application of this approach to a case study demonstrated that the results obtained by the advanced method were more accurate and comprehensive than those produced by the traditional method during risk assessments of chemical processes. The proposed method, combined with the fuzzy comprehensive evaluation and trapezoidal fuzzy number, is effective and practical to calculate the PFD of the emergency protection, which solves the problem of the determination of the failure probability of the emergency protection. Also, the proposed method can be applied generally in all chemical processes because the indexes system of emergency built in the paper is typical for general chemical processes. The fuzzy-AHP comprehensive evaluation and fuzzy set method are also operable when the judgments from experts can be done. Detailed rules and regulations during the indexes judgements will improve the accuracy of the result and lessen the subjective influence of experts. Furthermore, the calculation of the proposed method in this paper will be more convenient if all the calculations are programmed.

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