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Safety assessment of production process of styrene

WANG Fangfang, WANG Yajun*

State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

Abstract

Dow Fire and Explosion Index (F&EI) is employed to evaluate the safety of the styrene production unit. Both the inherent F&EI and the F&EI taking the Loss Control Measures (LCM) are calculated. The calculation results show that F&EI with LCM reduced 41.25% compared with inherent F&EI. Then, the Radius of Exposure and Area of Exposure are calculated, which refer to the probable damage range in case of fire and/or explosion. Last, the loss of the unit is calculated and the result is given in the term of dollars, which is direct and simple. The results can provide important information to managers, workers and residents around plants.

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Keywords: Dow Fire and Explosion Index (F&EI); safety assessment; styrene production unit; hazards rating

Nomenclature

| Symbol | Description                     |
|--------|---------------------------------|
| $F_1$  | general process hazards factor  |
| $F_2$  | special process hazards factor  |
| $F_3$  | process unit hazards factor     |
| $MF$   | materials factor                |
| $C_1$  | process control credit factor   |
| $C_2$  | material isolation credit factor|
| $C_3$  | fire protection credit factor   |
| $F&EI$ | Dow fire and explosion index    |

1. Introduction

With the continuous improvement of the productivity level, more and more attention was paid to the safety of plants. In the chemical industry, the principles of Inherently Safer Design (ISD) are implemented to prevent and limit risk of Chemical Process Industry (CPI) [1]. The integration of ISD into chemical process design and process optimization provides a tool to evaluate safety of chemical plants [2]. As a consequence, such processes that can both ensure health and safety of all involved in the plants and be environment-friendly are expected to reach [3].

To achieve an Inherently Safer Design (ISD), safety evaluation is essential. There are various methods can be employed to conduct safety evaluation. In general, these methods can be classified into two categories [4,5]: (a) Qualitative safety evaluation techniques, such as Preliminary Hazard Analysis (PreHA), Checklist, What-If Analysis, Hazard and Operability (HAZOP) Analysis, etc; (b) Quantitative safety evaluation techniques, such as Layer of Protection Analysis (LOPA), Dow Fire and Explosion Index (F&EI), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), etc. Each method has its special...
application. Among all the evaluation techniques, Dow Fire and Explosion Index (F&EI) is the most widely used in chemical process units.

Dow Fire and Explosion Index (F&EI) was first issued by American Dow Chemical Company in 1964, and so far, it has evolved to the 7th edition and has become a comprehensive index that gives a relative value to the risk of individual process unit losses due to the potential fires and explosions [6]. The F&EI method estimates the hazards of a single process unit based on the chemical properties and material inventories, and then uses plant construction cost or replacement cost to estimate the potential risk in dollars term [7]. The general calculation procedure is shown in Fig 1 [7,8].

![Fig.1. Procedure for calculating F&EI and other risk analysis information.](image)

2. Safety assessment of styrene production process unit

2.1. To determine the process unit

Styrene is one of the most important monomers for synthetic polymers. The world production at present is approximately 20 million tons per year. Styrene is mainly used for production of various different polymeric materials, such as polystyrene, styrene-acrylonitrile, acrylonitrile–butadiene–styrene (ABS), etc. The styrene process was developed by BASF (Badische Anilin-und-Soda-Fabrik) in Germany and Dow Chemical Company in USA in 1930s [9]. According to studies, the most important commercial production routes for styrene are the catalytic dehydrogenation of ethylbenzene (EB) to styrene and oxidation of EB to styrene [9]. However, up to 80% of styrene worldwide is produced through catalytic dehydrogenation of ethylbenzene (EB) to styrene. Since the reaction is limited by equilibrium, heavily endothermic, it is carried out in either adiabatic or isothermal mode in the fixed bed reactors. The process temperature is around 850 K and steam is added in the reactant to supply heat [10]. So it is easy to cause fires and/or explosions hazards in styrene production process unit.
2.2. To calculate F&EI

According to Fig 1, the calculation of safety of styrene process unit is carried out [6-8,11-13].

2.2.1. To determine the materials factor

Materials Factor (MF) which is a measure of the reactivity and flammability of materials is determined by NR (number of reactivity) and NF (number of flammability). MF is an important factor for F&EI. When the materials in the process unit are mixture, people usually choose the maximum MF as actual MF. As for the styrene process unit, NR and NF of styrene are respectively 2 and 3 (see relative figures [6]), and MF of styrene is 24, which is the max MF. So MF of the process unit is 24.

2.2.2. To determine the process unit hazards factors

The Process Unit Hazards Factor (F3) is the product of two parts: one is General Process Hazards Factor (F1), and the other is Special Process Hazards Factor (F2). So the equation to calculate F3 is as equation (1):

\[ F_3 = F_1 \times F_2 \]  
\[ (1) \]

The range of F3 is 1−8, if the calculated F3 is more than 8, thus F3 equals 8.

2.2.2.1. General Process Hazards Factor (F1).

F1 is the measure of reaction characteristics, and one of the important factors that define the F&EI value. F1 contains six items. Each item has a certain range, and if a certain item doesn’t exist, the value of this one is zero. F1 is the result of the basic value (which is 1.00) plus the value of each item. Due to low exothermic of the reaction, the item of the exothermic reaction (0.20 to 0.40) is 0.20; since the reaction is conducted in a closed container, the value of the enclosed or indoor process units (0.25 to 0.90) is 0.60; moreover, the access of the plant can be available, the value of the access (0.25 to 0.35) is 0.30; according to the process design, the other three items do not exist, thus the values of them are zero. So 
\[ F_1 = 1.00 + 0.20 + 0.60 + 0.30 = 2.10. \]

2.2.2.2. Special Process Hazards Factor (F2).

F2 is the measure of materials characteristics, and also one of the important factors that define the F&EI value. F2 contains twelve items. The calculation of F2 is the same as that of F1. Since styrene is toxic, the value of the toxic material (0.20 to 0.80) is 0.20; since the temperature of the reaction is high, the value of always in flammable range (0.80) is 0.80; while the pressure is low, so the value of the pressure (see relative figures [6]) is 0.30; due to the inventory of styrene is large, the value of the quantity of flammable/unstable material (see relative figure [6]) is 1.80; as for the production process of styrene, the other eight items do not exist, so the values of them are zero. So 
\[ F_2 = 1.00 + 0.20 + 0.80 + 0.30 + 1.80 = 4.10. \]

Thus:
\[ F_3 = F_1 \times F_2 = 2.10 \times 4.10 = 8.61. \]

Because the value of F3 is larger than 8, the actual F3 should be 8, that is \( F_3 = 8 \).

The calculation of F&EI is as following:

\[ F&EI = MF \times F_3 = 24 \times 8 = 192 \]  
\[ (2) \]

Based on Table 1 and the value of F&EI, the hazard rating of the process unit under discussion is the severe. This is the inherent hazards rating.

| F&EI index range | Degree of hazard |
|------------------|------------------|
| 1-60             | Light            |
| 61-96            | Moderate         |
| 97-127           | Intermediate     |
| 128-158          | Heavy            |
| 159-up           | Severe           |
2.3. To calculate the loss of the plant

The Radius of Exposure (ROE) and the Area of Exposure (AOE) demonstrate the range of the hazards if fire and explosion happen. To calculate these two items, engineers would refer to equations (3) and equation (4):

\[ ROE=0.3048 \times 0.84 \times F&EI=0.3048 \times 0.84 \times 192=49.16 \text{ m} \]  
(3)

\[ AOE=\pi \times ROE^2 = 3.14 \times 49.16^2 = 7588.46 \text{ m}^2 \]  
(4)

Then to calculate the base MPPD (base Maximum Probable Property Damage):

\[ \text{Base MPPD}=0.205939 \times F&EI^2 \times DF \times \text{value per unit area} \]

where, \( DF \) is so-called damage factor, which accounts for the actual damage experience based on \( MF \) and \( F_3 \):

\[ DF=f(MF, F_3)=0.88 \]

\[ \text{Base MPPD}=0.205939 \times 192^2 \times 0.88A=6680.73A \]

where, “A” refers to the value per unit area, dollars/m².

2.4. To determine the Loss Control Credit Factors

Loss Control Credit Factors refer to the loss control features and/or equipments that have been proved to be effective in preventing and limiting serious incidents. There are three categories of loss control features which are Process Control Credit Factor (\( C_1 \)), Material Isolation Credit Factor (\( C_2 \)) and Fire Protection Credit Factor (\( C_3 \)). The selection of penalties of each factor is explained in detail in reference [6]. The Factors used in the styrene process unit is listed in Table 2.

| Feature | Credit factor used |
|---------|--------------------|
| \( C_1 \) | 0.815 2 |
| \( C_2 \) | 0.931 0 |
| \( C_3 \) | 0.774 5 |
| \( LCCF \) | 0.587 8 |

The \( F&EI \) that take the \( LCCF \) into account (we call it as offset \( F&EI \)) is calculated due to the following equation:

\[ \text{Offset F&EI} = F&EI \times LCCF = 192 \times 0.5878 = 112.85 \]  
(5)

It can be seen that the hazard rating of the offset \( F&EI \) is intermediate, and it has reduced about 41.25%. It can be concluded that the offset \( F&EI \) is much safer than the \( F&EI \) without \( LCCF \). Hence:

\[ \text{Actual MPPD} = LCCF \times \text{Base MPPD}=0.5878 \times 6680.73A=3926.93A \]  
(6)

3. Results

According to the above calculation, the result of the safety evaluation of the styrene process unit can be summarized, which is shown in Table 3.

From Table 3, we can see that the \( F&EI \) has decreased by 41.25% from 192 to 112.85. The \( F&EI \) refers to the maximum probable hazards without any protection and limiting features or measures if fire and explosion occur. In fact, there are usually many facilities which called as protect layout, used to protect or limit the hazards in plants. So the actual \( F&EI \) should be lower than the inherent \( F&EI \). Moreover, with the reduction of the \( F&EI \), the hazards rating has also degraded from severe to intermediate, which means process unit is more safer than we image to be.
Table 3. Styrene process unit safety evaluation summary

| Item                                  | Value     |
|---------------------------------------|-----------|
| 1. F&EI                               | 192       |
| 2. Hazards rating                     | Severe    |
| 3. Radius of Exposure                 | 49.16 m   |
| 4. Area of Exposure (AOE)             | 7 588.46 m²|
| 5. Damage Factor                      | 0.88      |
| 6. Base MPPD                          | 6 680.73A |
| 7. Loss Control Credit Factor (LCCF)  | 0.587 8   |
| 8. Actual MPPD                        | 3 926.93A |

4. Conclusions

The safety of styrene process unit is evaluated according to the Dow Guide, and hazards rating and loss in terms of dollars of process unit are given as important information to plants engineers, managers and workers.

Through the comparison of the F&EI and the offset F&EI, we can conclude that LCCF is very important for the value of F&EI. F&EI refers to the inherent hazards of the process, while the offset F&EI is closer to the actual situation. The lower offset F&EI means the lower cost of the plant, such as shorter pipe, lower pressure drop, etc. Moreover, lower offset F&EI means the plant is safer than it would be like.

The results of the evaluation are provided in the dollars term, which can be much easier to be understood. Not only specialists and engineers, but also managers, workers in the pants and residents around the plants can have a clear understanding. It is benefit to conduct safety management.

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