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Risk assessment of an oxygen-enhanced combustor using a structural model based on the FMEA and fuzzy fault tree

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ABSTRACT

The oxygen-enhanced combustor has the advantages of high burning efficiency and low emissions. However, it should not be promoted for industrial use until its reliability and safety have been fully recognized. A new methodology is proposed to assess the risk of an oxygen-enhanced combustor using a structural model based on the FMEA and fuzzy fault tree. In addition, it is applied to a selected pilot semi-industrial combustor. To identify the hazard source comprehensively, the pilot is divided into four subsystems: the combustor subsystem, feed subsystem, ignition subsystem and exhaust subsystem. According to the operational parameters of flow (flow rate, temperature and pressure) and the component functions in different subsystems, the cause and effect matrix can be built using the structural model, and the relationship between the operational parameters and the effects of the change for the operational parameters on the system can be presented. Based on the results of cause and effect matrix, the FMEA can be built to describe the failed models and accident scenarios of the pilot. The main accident forms include leakage, injury, fire and explosion. Accordingly, with the severity and probability analysis of different accident forms, the fire and explosion accidents should be further accessed quantitatively using the fuzzy fault tree analysis. The fault trees can be obtained in accordance with the FMEA, and the qualitative assessments of the basic events can be collected by using expert scoring. A hybrid approach for the fuzzy set theory and weight analysis is investigated to quantify the occurrence probability of basic events. Then, the importance analysis of the fault trees, including the hazard importance of basic events and the cut set importance, is performed to help determine the weak links of the fire and explosion trees. Finally, some of the most effective measures are presented to improve the reliability and safety of the combustion system.

1. Introduction

As government emission standards become more stringent, a number of new clean combustion technologies are being investigated (Berggren and Magnusson, 2012; Cui et al., 2014). Oxygen-enhanced combustion (OEC) is known as one of the most promising combustion technologies (Wu et al., 2010) because it has several benefits over fuel–air combustion, such as a significant increase in thermal efficiency and flame stability, decrease in exhaust gas volume, and flue gas rich in CO_2, which enables easy CO_2 sequestration (Merlo et al., 2014; Sánchez et al., 2013).

In the general context of research that improves combustion efficiency and reduces pollutants (Yuan et al., 2014), an oxygen-enhanced combustion process has been designed (Qin, 2013; Qin et al., 2013). The hazards associated with using the pilot combustor are various and are related to different sources. Obviously, it is related to the fuel (inflammable gas) and to the burning condition of the combustor (high temperature and high pressure). In addition, there may be hazards from the fuel storage to the combustion process. The main risks associated with using the oxygen-enhanced combustor are leakage, fire, explosion and human injury (Thivel et al., 2008).

Various methodologies have been proposed for the purpose of a comprehensive and accurate risk analysis in the industrial process (Tixier et al., 2002). Several of these methodologies are qualitative, such as the failure mode and effect analysis (FMEA) (Pillay and Wang, 2003) and hazard and operability analysis (HAZOP)

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(Venkatasubramanian and Viswanathan, 2000); others are quantitative, such as the fault tree analysis (FTA) (Rauzy, 1993; Lee et al., 1985) and bow-tie analysis (BTA) (Khakzad et al., 2012). Although different methods consist of different steps and follow specific procedures, hazardous materials' identification occurs in terms of both the mechanism and likelihood of a common and central step to all of them (Nolan, 2014). Based on the results of hazard identification, reasonable accident scenarios can be proposed to reveal the potential risk in the industrial process.

To evaluate the reliability of process industries efficiently, many researchers have proposed various improvements to advance the risk assessment method. Narapan Boomthum (Boomthum et al., 2014) combined the automatic HAZAOP analysis with a structural model and obtained a systematic procedure for hazard and maloperations identification. P.-X Thivel (Thivel et al., 2008) presented a risk analysis method using the MOSAR and FMEA to identify hazard sources for a semi-industrial pilot and analyzed in detail the major risks identified from different stages. Daqing Wang (Wang et al., 2013) investigated a hybrid approach for the fuzzy set theory and FTA to quantify the crude oil tank fire and explosion in a fuzzy environment and to evaluate the accident occurrence probability.

On the basis of previous studies, the present work was aimed at assessing the risk of a semi-industrial OEC pilot by using a new methodology. In the methodology, the build process of the FMEA was combined with a structural model. The hazards identification and accident scenarios identification could be finished by the structural model-based FMEA, and then the fault tree of the main accident forms could be built. The probabilities of the basic events were treated as a fuzzy number, which could be obtained by expert elicitation and the theory of fuzzy logic. Finally, the most important basic event and minimal cut sets were found, and some simple and efficient adaptations were proposed to improve the safety of the system.

2. Methodology

2.1. Structural model-based FMEA

The failure mode and effect analysis is one of the important methods in safety system engineering. It was developed on the basis of reliability engineering, which is used to analyze the reliability and safety of systems, processes and productions. The main analysis steps include decomposing the system, investigating the subsystems sequentially and finding the potential failure models of components. Then, we can present all of the accident forms and proposed measures to improve the reliability and safety of the systems, processes and productions (Cicek and Celik, 2013). With the advantage of understandability and convenience, the FMEA is widely available in industrial processes. However, the drawbacks of the FMEA are the need for intense expert knowledge and time consumption. Moreover, it cannot be used to consider the interactions among the human–machine–environment (Lin et al., 2014). Therefore, a hybrid methodology is proposed with the combination of a structure model and FMEA. The sound system analysis function of the model can make up for the drawbacks of the FMEA effectively. In addition, the cause and effect matrix (CEM) based on a structural model can improve the efficiency of the design and analysis of the FMEA for a system (Snooke and Chris Price, 2012) and promote the completeness and sufficiency of the analysis process.

A structural model was defined by Lin (Lin, 1991) that uses a matrix to express the relationship among all variables in a system (Reinschke and Wiedemann, 1997). Further modifications have been suggested by several authors (Chang and Yu, 1990; Wang et al., 2009; Huang, 2013), and one development of this model is used to analyze the controllability of the process that is the so-called output structural controllability (OSC) (Hopkins et al., 1998). The modification form reveals the loop control pairing for a system.

The description of the structural model is derived from the linear time-invariant system as (Lin, 1991):

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{1}$$

where x is the n-dimensional state variable vector, u is the m-dimensional manipulated variable vector or input variables, and y is the r-dimensional output variable or control objective vector. A, B, C, and D are the matrices and can be either quality or quantity.

Structural matrix A is a matrix having fixed zeros in a certain location and arbitrary entries (denoted by X) in the remaining locations instead of numeric values. An X placed at the junction of a row and a column indicates that the column variable affects the row variable in some manner. A structural system can then be formulated as a matrix for an r–m matrix called the cause and effect matrix (CEM) (Lin, 1991). The CEM can be formulated for r outputs and m manipulated inputs. For example, the structural system s (the right side of Equation (2)) is an ordered pair of structural matrices, which is consistent with the description in Equation (2).

$$\begin{array}{c} \\ \dot{x}1 \\ \dot{x}2 \\ y1 \\ y2 \end{array} \begin{array}{c} \begin{array}{cccc} x1 & x2 & x3 & x4 \end{array} \\ \begin{pmatrix} X & 0 & X & 0 \\ 0 & X & 0 & X \\ X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \end{pmatrix} \end{array} \Longrightarrow S = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{2}$$

The CEM is an important analysis tool used to determine the output structural controllability. Additionally, it is a structural matrix that represents the dynamic relationships between the chosen manipulated variables and control objectives. However, the CEM cannot present a complete picture of causality. The 'path' or 'relationships' form input to output shown in the CEM must be independently accessible. The insufficient paths can be offset by 'tracing' paths from the inputs through the states to the outputs through the structural matrix. These paths may interconnect to form a network. Problems arise when an output cannot be accessed by an input through an independent path. That is, the output is not independently accessible. John and Barton identified three forms of defective structures that will affect the controllability. They are shown below (Johnston et al., 1985a,b):

- Defective Structure Type I: Contractions in the cause and effect relationships between manipulated and outputted variables.
- Defective Structure Type II: Lack of access to some or all of the outputs from the available manipulated variables.
- Defective Structure Type III: Access to one or more control objectives via other control objectives.

2.2. Fuzzy fault tree analysis

The fault tree is a logical tree that is generated from the results for the cause of the accident. The fault tree follows logical analysis principles (analyzed from the consequences to the cause), and the related events (nodes) are connected with logic gates. This method is called the fault tree analysis and can predict accidents using a fault tree.

In traditional fault tree analyses (FTA), the failure probabilities of the basic events are expressed by exact values in the quantitative analysis and by random values (1 or 0) in the qualitative analysis (Purba et al., 2011; Volkanovski et al., 2009). However, to ascertain the exact values of the failure probabilities, sufficient statistical inference is needed. Moreover, both the changing working environment and the fuzzy feature of the system raise difficulties in the estimation of exact probabilities for the basic events (Dong and Yu, 2005). On the other hand, the calculation error with random values is large, and it hardly satisfies the demand in reality. To handle the inevitably imprecise failure information in diversified real applications, many studies have taken uncertain situations into consideration. The fuzzy set theory has proven to be effective for solving the problems when there are no regular boundaries and precise values (Liang and Wang, 1993; Mon and Cheng, 1994). Therefore, it is applied to the reliability analysis and system safety to estimate the failure probabilities of basic events.

The concept of fuzzy set theory was introduced by Zadeh (1965) to handle uncertain or vague information. A fuzzy set takes values from the interval [0, 1] and is characterized by a membership function $\mu(x)$, which represents the relationship among different elements. Fuzzy sets are defined for specific linguistic variables, which can be calculated by triangular fuzzy numbers (TFNs) or trapezoidal fuzzy numbers (ZFNs). The TFNs are denoted by a triplet ($a1$, $a2$, and $a3$) and the ZFNs are denoted by a triplet ($a1$, $a2$, and $a3$) and a quadruple ($a1$, $a2$, $a3$, and $a4$) and can be defined as follows (Kumar and Yadav, 2012):

$$\text{TFNs}: \quad \mu(x) = \begin{cases} 0; & x \le a_1 \\ (x-a_1)/(a_2-a_1); & a_1 \le x \le a_2 \\ (a_3-x)/(a_3-a_2); & a_2 \le x \le a_3 \\ 0; & x \ge a_3 \end{cases} \tag{3}$$

$$\text{ZFNs}: \quad \mu(x) = \begin{cases} 0; & x \le a_1 \\ (x-a_1)/(a_2-a_1); & a_1 \le x \le a_2 \\ 1; & a_2 \le x \le a_3 \\ (a_4-x)/(a_4-a_3); & a_3 \le x \le a_4 \\ 0; & x \ge a_4 \end{cases} \tag{4}$$

2.3. The new methodology for risk analysis

An overall analytical methodology is proposed to allow the analysis and calculation of the risk for the oxygen-enhanced combustor or some analogous system. The new risk analysis method is built on the basis of a structural model-based FMEA and fuzzy fault tree analysis. The main procedures of the risk assessment method consist of the following steps.

(1) System analysis

After surveying the system and collecting the related information, the system can be divided into the technical process, production organization and protection management. Based on the previous accident records, the hazard of the system/subsystem can be identified preliminarily.

(2) Signed digraph analysis for the system/subsystem

To formulate the structural model from the relevant parameters (such as flow rate, temperature, and pressure) of the system/subsystem, four main types of parameters are considered. The first is "xn", referring to the state number "n". The second is "un", referring to all possible consequences of the state number "n". The third "yn" refers to all possible consequences of the state number "n". The last is "n", which is the order of the states.

Considering the selected system/subsystem, the signed digraph is used to represent the relationships between the causes, consequences and system/subsystem variables. Then, the analysis of the relationships among those parameters can be represented by using the digraph form.

(3) Cause and effect matrix (CEM)

From the signed digraph, the relationships based on the general heat and mass balances can be revealed by the concept of a structural model. Meanwhile, the main hazard and accident forms can be listed from the CEM.

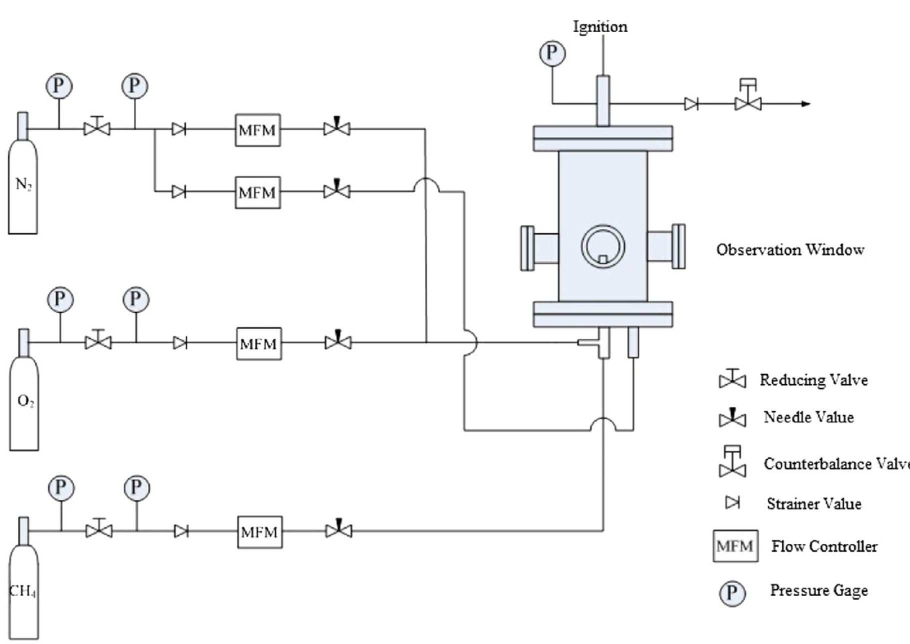


Fig. 1. Outline of the pilot (Qin, 2013).

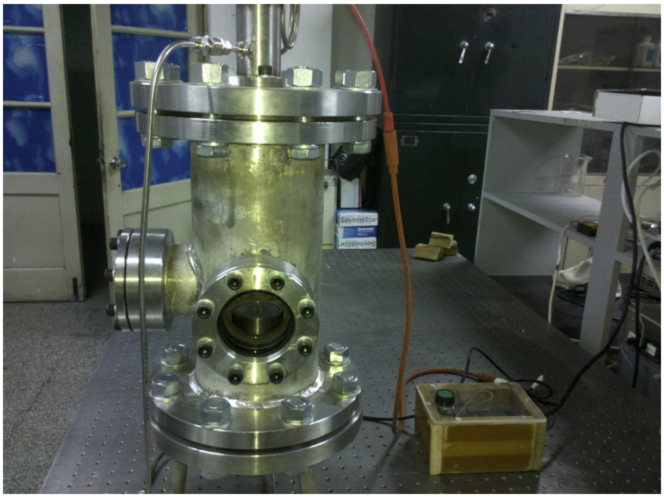


Fig. 2. Installation drawing for a combustor (Qin, 2013).

(4) Structural model-based FMEA

According to the results of the hazard identification, the FMEA of the system/subsystem can be built. For every FMEA, there should be failure models, effects, occurring conditions and detection methods. In addition, the risk of the system/subsystem can be analyzed qualitatively, while the main risk forms should be further studied quantitatively.

(5) Fuzzy fault tree for major accidents

The fuzzy fault tree and traditional tree have a similar construction method. The failure probability of the basic events can be assessed by using expert scoring. A hybrid approach for the fuzzy set theory and weight analysis can be applied to quantify the occurrence probability of basic events. Then, the importance analysis of the fault trees, including the hazard importance of the basic events and cut set importance, is performed to help determine the weak links of the fire and explosion trees.

(6) Risk assessment and improvement

According to the results of the fuzzy fault tree, the risk assessment for different accident forms can be proposed, and some measures can be erected to improve the safety of the system.

3. Description of the pilot

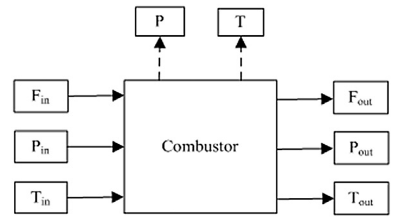
An overall analytical procedure is proposed to allow the analysis and calculation of the risk for the selected pilot or some analogous system. The selected pilot is a semi-industrial oxygen-enhanced combustor, composed of a fuel/O_2 supply device, pressure combustor, control system and detection device. The pilot and combustor design are shown as Figs. 1 and 2, respectively. The fuel and gas (CH_4, O_2 and N_2) pass through the reducing valve and strainer value and into the flow controller. Then, the mixture gas of O_2 and N_2 enter into the oxidizing agent pipeline, while CH_4 enters into the fuel pipeline. When ignition succeeds, N_2 passes through the pressurizing pipeline into the combustor to enhance the combustion pressure. On the other hand, the counterbalance valve in the opening of the exhaust device can also take the role of regulating the pressure, and the pressure in the combustor can be recorded by the pressure gage. The combustion product passes through the counterbalance valve into flue gas analyzer.

Table 1
Subsystems and their components.

ID	Subsystem	Components
1	Combustor subsystem	Cylindrical combustor, Flange, Observation Window
2	Feed subsystem	Gas tank, Pressure gage, Reducing valve, Flow Controller, Needle value, Strainer value, Pipeline
3	Ignition subsystem	Ignition, Pressure gage
4	Exhaust subsystem	Strainer value, Counterbalance valve, Pipeline

Table 2
List of relevant parameters for the combustor subsystem.

Flow diagram



Parameters	Sign	Refer to	Parameters	Sign	Refer to
F_{in}	x1	Input flow rate	F_{out}	x2	Output flow rate
P_{in}	x3	Input pressure	P_{out}	x4	Output pressure
T_{in}	x5	Input temperature	T_{out}	x6	Output temperature
P	x7	Combustor pressure	T	x8	Combustor temperature

4. Application of the methodology

4.1. CEM of different subsystems

To identify the type of hazard source and to define the hazardous processes comprehensively, the pilot is divided into four subsystems based on the previous description as shown in Table 1.

In order to visualize how to build signed digraph, CEM and FMEA, the following Table 2 shows the example of the combustor subsystem step by step.

All of the stared parameters refer to the rate of change for these variables. For example, X4*, which denoted the rate of change for the output stream pressure, is affected by state “x3” (refers to the input stream pressure), “x4” (refers to the output stream pressure), “x7” (refers to the combustor pressure) and “x8” (refers to the combustor temperature). It could be expressed as X4* = *f*(x1,x2,x7,x8), and all of such relationships for the combustor subsystem are listed in Table 3.

Table 3
The relationships among all of the states for the combustor subsystem.

The parameter for the rate of change for each state	The parameters that affect the rate of change for each state
X1*	*f*(x1)
X2*	*f*(x1,x2)
X3*	*f*(x3)
X4*	*f*(x3,x4,x7,x8)
X5*	*f*(x5)
X6*	*f*(x5,x6,x7,x8)
X7*	*f*(x1,x2,x3,x4,x5,x6,x7)
X8*	*f*(x1,x2,x3,x4,x5,x6,x8)

$$\begin{pmatrix}\dot f_2\\ \dot f_4\\ \dot f_6\\ \dot f_7\\ \dot f_8\end{pmatrix}=\begin{pmatrix}\times&0&0&0&0\\0&\times&0&\times&\times\\0&0&\times&\times&\times\\\times&\times&\times&\times&0\\\times&\times&\times&0&\times\end{pmatrix}\begin{pmatrix}f_2\\f_4\\f_6\\f_7\\f_8\end{pmatrix}+\begin{pmatrix}\times&0&0\\0&\times&0\\0&0&\times\\\times&\times&\times\\\times&\times&\times\end{pmatrix}\begin{pmatrix}f_1\\f_3\\f_5\end{pmatrix}\Rightarrow\begin{array}{c}\\f_2\\f_4\\f_6\\f_7\\f_8\end{array}\begin{array}{c}\begin{matrix}f_1&f_3&f_5\end{matrix}\\\begin{pmatrix}\times&0&0\\0&\times&0\\0&0&\times\\\times&\times&\times\\\times&\times&\times\end{pmatrix}\end{array}$$

Fig. 3. CEM of a combustor subsystem.

Table 4
Potential failure models in the combustor subsystem.

ID	Model	Description
1	$u_1 \to x_1 \overset{\oplus}{\to} x_2 \to y_4$	Input flow rate increases, and many smoke particles are generated because of incomplete combustion. High flow rates blow out the flame and lead to gas accumulation.
2	$u_3 \to x_3 \overset{\oplus}{\to} x_4 \to y_4$	Output pressure is enhanced due to overpressure at the input, which leads to exhaust subsystem failure.
3	$u_5 \to x_5 \overset{\oplus}{\to} x_6 \to y_6$	Output temperature elevates because of an over temperature at the input, which decreases the yield strength of the pipeline.
4	$\left.\begin{matrix}u_1\to x_1\\u_3\to x_3\\u_5\to x_5\end{matrix}\right\}\overset{\oplus}{\to}x_7\to y_7$	Input flow rate increases, while the pressure and temperature increase, which leads to a combustor explosion.
5	$\left.\begin{matrix}u_1\to x_1\\u_5\to x_5\end{matrix}\right\}\overset{\oplus}{\to}x_8\to y_8$	Input flow rate increases, while the pressure increases, which decreases the yield strength of the combustor.

After obtaining the relationships among all of the states for the combustor subsystem, the CEM based on the concept of a structural model can be generated, as shown in Fig. 3.

From the CEM of the combustor subsystem, we can obtain the failure models of different accidents, and the descriptions of the CEM are shown in Table 4.

4.2. FMEA of the pilot

By the same method, the CEM of the other three subsystems can be obtained as shown in Appendix B. According to the CEMs of the subsystems and the corresponding failure model, we can design the FMEA of the pilot, as shown in Table 5.

From the FMEA in Table 5, the main accident forms of the pilot include leakage, injury, fire and explosion. Accordingly, with the severity and probability analysis of different accident forms (Thivel et al., 2008), the fire and explosion accident should be further accessed quantitatively using the fuzzy fault tree analysis.

4.3. FTA for fire and explosion accidents

According to the FMEA of the pilot, tank explosion accidents may be caused by overpressure, yield strength reduction and mechanical stress, and it most likely happens in the cylindrical combustor. Fuel leaked and then ignited, which is the potential path for a fire accident. On the basis of the results for the accidents forms in Table 4 and Appendix A, the fault tree can be built easily as shown in Figs. 4 and 5.

Because it was considerably difficult to obtain the precise probability data for all basic events of the fault tree for fire and explosion, the expert scoring method (ESM) (Trucco and Cavallin, 2006) was proposed to describe the occurrence possibilities of the basic events in the paper. There are four experts to assess the risk of basic events, and the detailed information from the experts is shown in Appendix B. According to the possibility value of every event, there are seven scoring levels: very low (VL), low (L), mildly low (ML), medium (M), mildly high (MH), high (H) and very high (VH). The membership functions for the different scoring levels are shown in Fig. 6 (Pinto, 2014).

For the same system, every expert has a different view and assessment of the basic events. For convenience in additional calculations, the scores of all experts must be transformed into a quantitative value. Many researchers have studied how to process expert information, and the current method used is the analytic hierarchy process (AHP) to calculate the weight factor of different experts. Combined with the fuzzy set method, a new fuzzy number can be aggregated on the basis of expert information for a basic event, and then it is transformed into a fuzzy failure rate (Shi et al., 2014; Renjith et al., 2010).

A consistency aggregation method (Wei et al., 2001) is used in this paper, which could be used for consistency among these various qualitative decisions. The results of the four experts' scores for all basic events are shown in Table 6.

It is a crucial task to identify the most important basic event and minimal cut sets from a risk assessment viewpoint so that several priority actions can be proposed to improve the safety of the system. Based on the results for the basic events, the importance analysis of the fault trees, including the hazard importance of the basic events and the cut set importance, the occurrence probability can be performed to help in developing the qualitative assessments

Table 5
FMEA of oxygen-enhanced combustor system.

Subsystem ID	Failure models	Causes	Effect	Detection
Combustor Subsystem	Leakage	Reducing valve failure Mechanical stress	Fuel accumulation and the formation of an explosive atmosphere Unstable combustion	Ensure gas is available Observe the pressure gage
	Explosion	Reducing valve failure Yield strength reduction Mechanical stress	Combustor explosion Pressure gas leakage	Observation
Feed Subsystem	Leakage	Pressure gage failure Seal or joint failure	Fuel accumulation and the formation of an explosive atmosphere	Ensure gas is available Observe the pressure gage
	Overpressure	Pressure gage failure Reducing valve failure	Pressure disorder in the combustor	Observe the pressure gage
	Excess flow rate	Flow controller failure Incorrect operation	Fuel accumulation and the formation of an explosive atmosphere	Observe the flame
	Blockage	Strainer valve failure	Unstable combustion	Ensure gas is available
Ignition Subsystem	Ignition failure	Ignition failure	Ignition Failure and fuel accumulation	Observe the flame
	Accidental ignition	Incorrect operation	Forming fire resource	Observe the ignition
Exhaust subsystem	Overpressure in output	Counterbalance failure	High temperature and pressure gas leakage	Observe the pressure gage
	Leakage	Seal or joint failure		Ensure gas is available Observe the pressure gage

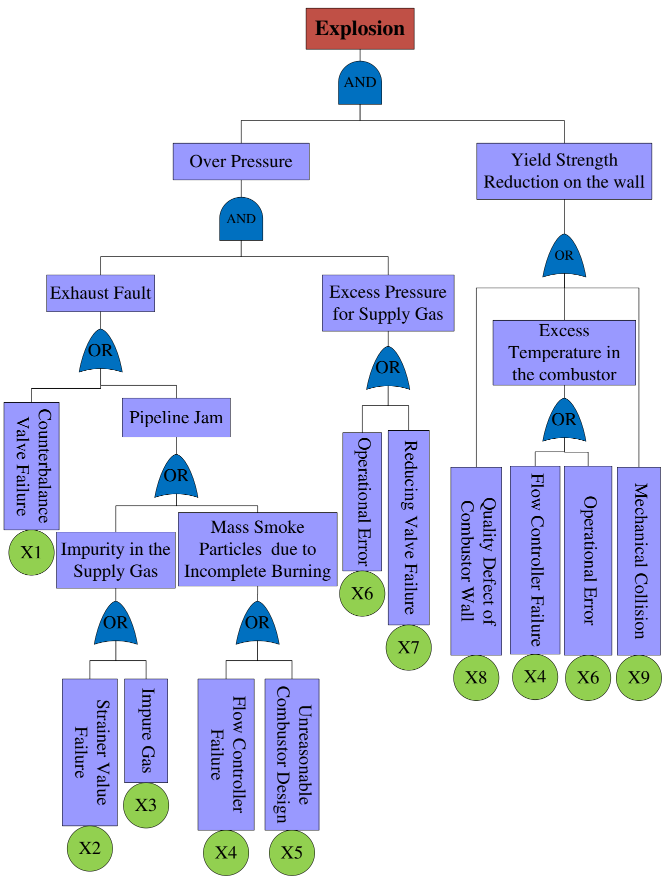


Fig. 4. FAT for an explosion accident.

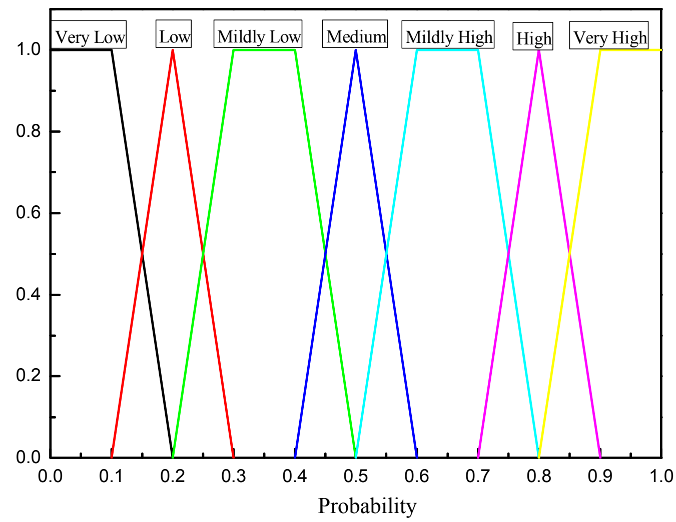


Fig. 6. Fuzzy number sets for expert scores.

for fire and explosion trees. The hazard importance of the two FATs is shown in Table 7.

For large and complex trees, the minimal cut sets can be calculated by solving the related success tree. Because the tree in this study is relatively simple, the minimal cut sets can be obtained by using a Boolean operation. Then, the importance of every minimal cut set can be completed based on the probabilities of the basic events (BEs) in Table 6. Cut set importance (CS-I) is used to evaluate the contribution of each minimal cut set versus the top event occurrence probability. The CS-I provides a method for ranking the impact of each minimal cut set and for identifying the most probable accident forms. The calculation of CS-I is performed in equation (5), and the results are shown in Table 8:

$$\mathrm{CS}-\mathrm{I}(j) = P_{\mathrm{MCS}(i)}/P_{\mathrm{TE}} \tag{5}$$

where $\mathrm{CS}-\mathrm{I}(j)$ is the importance of the jth minimal cut set; $P_{\mathrm{MCS}(i)}$ is the occurrence probability of the jth minimal cut set; and P_{TE} is the occurrence probability of the top event.

From Table 8, three of the top MCSs are: {X5, X7, X9}, {X3, X6} and {X5, X7, X8} for the explosion accident and {X10, X12}, {X7, X12} and {X2, X6} for the fire accident.

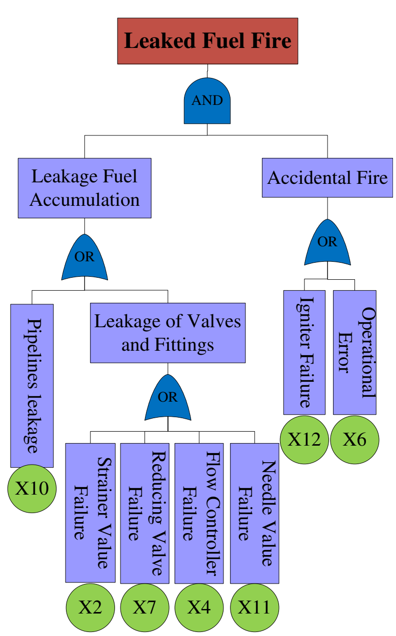


Fig. 5. FAT for a fire accident.

5. Results and discussion

According to the results listed in Table 7, three of the top BEs are: X3 (impure gas, 2.69E-03), X6 (operational error, 1.57E-04), and X7 (reducing valve failure, 3.94E-04), respectively, which are obtained by using a hybrid approach for the fuzzy set theory and weight analysis. In the explosion tree, the BEs are X6 (operational error, 0.1868), X3 (impure gas, 0.09429) and X2 (strainer value failure, 0.0745) in order of hazard importance, while X7 (reducing valve failure, 0.384), X2 (strainer value failure, 0.2469) and X4 (flow controller failure, 0.1753) are for the fire tree. From the pilot system, the occurrence probabilities for the fire and explosion accidents are 1.706E-03 and 5.325E-03, respectively, and X6 (operational error) is the most hazardous basic event for the system safety.

Based on the previous results, the most probable route to the explosion accident is {X5, X7, X9}, which denotes an unreasonable combustor design, a reducing valve failure and a mechanical collision. This combination leads to a combustor explosion due to excessive pressure easily. Then, the potential routes {X3, X6} and {X5, X7, X8} form the view for the occurrence probability. Accordingly, for the fire accident, the most probable route to the explosion accident is {X10, X12}, which is the combination of pipeline leakage and igniter failure, and then is {X7, X12} and {X2, X6}, respectively.

Table 6
Scores and probability values for 43 basic events.

NO.	Basic event	Expert scoring				Fuzzy number sets	FPS	FFR
		# 1	# 2	# 3	# 4			
X1	Counterbalance Valve Failure	VL	L	L	VL	(0.072,0.09,0.145,0.245)	0.1556	9.04E-05
X2	Strainer Value Failure	L	VL	VL	L	(0.195,0.156,0.178,0.278)	0.2075	2.53E-04
X3	Impure Gas	M	ML	ML	L	(0.495,0.335,0.38,0.48)	0.4176	2.69E-03
X4	Flow Controller Failure	VL	L	L	L	(0.072,0.14,0.17,0.27)	0.1883	1.8E-04
X5	Unreasonable Combustor Design	L	VL	VL	L	(0.342,0.278,0.356,0.456)	0.3558	1.42E-04
X6	Operational Error	ML	ML	L	ML	(0.195,0.2,0.2,0.3)	0.2359	1.57E-04
X7	Reducing Valve Failure	L	L	VL	VL	(0.072,0.05,0.125,0.225)	0.1278	3.94E-04
X8	Quality Defect of Combustor Wall	VL	VL	VL	L	(0.072,0.096,0.148,0.248)	0.1596	4.32E-05
X9	Mechanical Collision	VL	L	VL	VL	(0.072,0.096,0.148,0.248)	0.1596	9.93E-05
X10	Pipeline Leakage	VL	L	VL	L	(0.072,0.094,0.147,0.247)	0.1583	9.93E-05
X11	Needle Value Failure	VL	VL	VL	L	(0.072,0.094,0.147,0.247)	0.1583	9.63E-05
X12	Igniter Failure	VL	VL	L	VL	(0.195,0.11,0.155,0.255)	0.1761	9.63E-05

Marks: FPS, Fuzzy Possibility Scores; FFR, Fuzzy Failure Rates.

Table 7
The hazard importance of the FATs for fire and explosion.

Ranking of BEs			FTA for explosion			FTA for fire		
BEs	FFR	Ranking	BEs	HI	Ranking	BEs	HI	Ranking
X1	9.04E-05	11	X1	0.02662	6	X2	0.2469	2
X2	2.53E-04	4	X2	0.07455	3	X4	0.1753	3
X3	2.69E-03	1	X3	0.09429	2	X6	0.0942	6
X4	1.8E-04	5	X4	0.06627	4	X7	0.384	1
X5	1.42E-04	6	X5	0.04166	5	X10	0.09674	5
X6	1.57E-04	2	X6	0.1868	1	X11	0.09681	4
X7	3.94E-04	3	X7	0.01334	7	X12	0.05783	7
X8	4.32E-05	12	X8	0.000101	9			
X9	9.93E-05	7	X9	0.000233	8			
X10	9.93E-05	8						
X11	9.63E-05	9						
X12	9.63E-05	10	PTB of Explosion, 5.325E-03			PTB of fire, 1.706E-03		

Marks: BEs, Basic Events; HI, Hazard importance; PTB, probability of the top event.

For the semi-industrial combustor, the accident forms vary from the calculation of the MCS, and the most likely events leaded to explosion are ‘an unreasonable combustor design’ and a ‘reducing valve failure’. Thus, the effective measures to improve the system reliability and safety include revising the design of the combustor, raising the reliability of the accessories and enhancing the welding quality. In practice, the operator should pay attention and observe the pressure gage. Once pressure is disordered, the operator must suspend the feed subsystem and determine the reason for the pressure disorder.

In addition, the operator should inspect the weld and joint between the pipelines, values and fittings, especially for the CH_4 supply line. Then, the operator should improve the reliability of ignition, operate the pilot, follow the rules and avoid an accidental ignition.

6. Conclusion

Although the classical FMEA and FTA analyses are practically used for risk analysis in industrial processes, the drawback is the need for intense expert knowledge and substantial time consumption. The proposed methodology in this work can fulfill the analyzers by using the cause and effect matrix of the pilot system, especially for inexperienced analyzers.

According to the operational parameters of flow (flow rate, temperature and pressure) in different subsystems, the cause and effect matrix can be built using a structural model, and the relationship between the operational parameters and the effects of the change for the operational parameters on the system can be represented. Thus, we can study the causes and the development models for accidents at a deep level. Based on the results of the cause and effect matrix, the FMEA can be built to describe the failed models and accident scenarios of the pilot. The FMEA is one of the importance results in this paper, which could be treated as the basis for regulations for safety operations and further risk assessment. The most hazardous accidents would be further accessed quantitatively using the fuzzy fault tree analysis in accordance with the FMEA.

Table 8
The results of the CS-I for each minimal cut set.

CS-I for explosion FTA				CS-I for fire FTA			
Number	Minimal path sets	CS-I	Ranking	Number	Minimal path sets	CS-I	Ranking
1	{X1, X6}	2.53E-10	10	1	{X2, X6}	5.3E-06	3
2	{X1, X7, X8}	5.8E-10	8	2	{X2, X12}	2.92 E-06	4
3	{X1, X7, X9}	9.02E-11	12	3	{X4, X6 }	1.79E-07	8
4	{X2, X6}	9.02E-11	13	4	{X6, X7}	4.58E-07	7
5	{X2, X7, X8}	1.41E-10	11	5	{X6, X10}	7.12E-07	6
6	{X2, X7, X9}	3.24E-10	9	6	{X6, X11}	1.74E-07	9
7	{X3, X6}	2.33E-05	2	7	{X7, X12}	7.46E-06	2
8	{X3, X7, X8}	4.15E-06	5	8	{X10, X12}	1.16E-05	1
9	{X3, X7, X9}	2.68E-09	7	9	{X11, X12}	284E-06	5
10	{X4, X7}	6.16E-09	6				
11	{X5, X6}	8.31E-06	4				
12	{X5, X7, X8}	1.30E-05	3				
13	{X5, X7, X9}	2.47E-04	1				

The methodology is applied to a selected pilot semi-industrial combustor for the risk assessment. First, the pilot is divided into four subsystems, and the CEMs of the four subsystems are built by analyzing the relationship between the operational parameters and the effects of the change for the operational parameters on the system. Based on the results of the cause and effect matrix, the FMEA can be built to describe the failed models and accident scenarios of the pilot. Then, we know that there are four potential accident forms for the pilot: leakage, injury, fire and explosion. Among these forms, the most hazardous are fire and explosion. Thus, the two accident forms are further accessed quantitatively using the fuzzy fault tree analysis in accordance with the FMEA.

From the results of this study, the occurrence probabilities of fire and explosion are 5.325E-03 and 1.706E-03, respectively, and three of the top MCSs are {X5, X7, X9}, {X3, X6} and {X5, X7, X8} for the explosion accident and {X10, X12}, {X7, X12} and {X2, X6} for the fire accident. Finally, several of the most effective measures are proposed to improve the reliability and safety of the combustion system.

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Appendix A

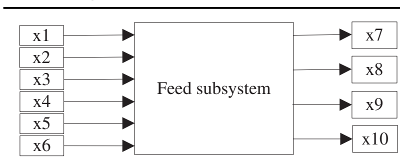
We treat valves and fittings as manipulated variables and treat accident forms as manipulated variables because there are so many valves and fittings in the feed subsystem. The CEM of the feed subsystem can be built based on the relationships between the components and system failure models. The results are shown as follows.

$$\begin{array}{c|cccccc} & f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \\ \hline f_7 & \times & \times & \times & \times & \times & \times \\ f_8 & 0 & \times & 0 & \times & 0 & 0 \\ f_9 & 0 & 0 & 0 & 0 & \times & \times \\ f_{10} & \times & 0 & \times & 0 & 0 & 0 \end{array}$$

Fig. 7. CEM of a feed subsystem.

Table 9
List of relevant parameters for the feed subsystem.

Flow diagram



Parameters/Sign	Refer to	Parameters/Sign	Refer to
x1	Gas Tank	x2	Reducing Valve
x3	Strainer Value	x4	Pressure Gage
x5	Needle Value	x6	Flow Controller
x7	Leakage	x8	Overpressure
x9	Overflow	x10	Impure

Table 10
The relationships among all of the states for the feed subsystem.

The parameter for the rate of change for each state	The parameters that affect the rate of change for each state
X1*	f(x1)
X2*	f(x2)
X3*	f(x3)
X4*	f(x4)
X5*	f(x5)
X6*	f(x6)
X7*	f(x1,x2,x3,x4,x5,x6,x7)
X8*	f(x2,x4,x8)
X9*	f(x5,x6,x9)
X10*	f(x1,x3)

After obtaining the relationships among all states for the combustor subsystem, the CEM based on the concept of a structural model can be generated.

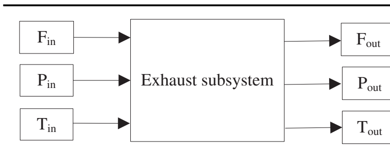
The analysis process of the exhaust subsystem CEM is analogous to the combustor subsystem. We treat input flow parameters as manipulated variables and treat output flow parameters as manipulated variables. The CEM of the exhaust subsystem can be built based on the relationships between the operational parameters and the effects of the change for the operational parameters on the subsystem. The results are shown as follows.

$$\begin{array}{c|ccc} & f_1 & f_3 & f_5 \\ \hline f_2 & \times & \times & 0 \\ f_4 & 0 & \times & 0 \\ f_6 & \times & \times & \times \end{array}$$

Fig. 8. CEM of an exhaust subsystem.

Table 11
List of relevant parameters for the exhaust subsystem.

Flow diagram



Parameters	Sign	Refer to	Parameters	Sign	Refer to
F_{in}	x1	Input flow rate	F_{out}	x2	Output flow rate
P_{in}	x3	Input pressure	P_{out}	x4	Output pressure
T_{in}	x5	Input temperature	T_{out}	x6	Output temperature

Table 12
The relationships among all of the states for the exhaust subsystem.

The parameter for the rate of change for each state	The parameters that affect the rate of change for each state
X1*	f(x1)
X2*	f(x1,x2,x3,x5)
X3*	f(x3)
X4*	f(x1,x3,x4,x5)
X5*	f(x5)
X6*	f(x1,x3,x5,x6)

After obtaining the relationships among all states for the combustor subsystem, the CEM based on the concept of a structural model can be generated.

The ignition subsystem has a simple structure and no flow through. The CEM and its illustration are shown in Table 13.

Table 13
List of relevant parameters for the ignition subsystem.

Flow diagram			
$\begin{matrix} & f_1 & f_3 \\ \begin{matrix} f_2 \\ f_4 \end{matrix} & \multicolumn{2}{c}{\begin{pmatrix} \times & 0 \\ 0 & \times \end{pmatrix}} \end{matrix}$			
Parameters	Refer to	Parameters Sign	Refer to
f_1	Ignition Failure	f_2	System Failed
f_3	Accidental Ignition	f_4	Fire source

Appendix B

Table 14
List of relevant parameters for the ignition subsystem.

Name	Title	Unit name	Address	E-mail
Li Zhen	Ph.D	Tsinghua University	Beijing, China	cz1351966016@126.com
Zhang Miao	Engineer	Tianjin public security fire brigades	Tianjin, China	370443710@qq.com
Wang Ji	Lecturer	Chinese people's armed police force academy	Heibei, China	Hutty_wang@126.com
Qin Jianguo	Engineer	East China electric power institute of China power engineering consulting group	Shanghai, China	237718325@qq.com

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