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

Zhen Chen [a,*], Xiaona Wu [b], Jianguo Qin [c]

[a] Institute of Mechanics, Chinese Academy of Sciences, 100190 Beijing, China
[b] School of Environmental Science and Engineering, Tianjin University, 300072 Tianjin, China
[c] East China Electric Power Institute of China Power Engineering Consults Group, 200063 Shanghai, China

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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)

* Corresponding author.
E-mail address: chenzhen@imech.ac.cn (Z. Chen).

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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