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A framework and method for the assessment of inherent safety to enhance sustainability in conceptual chemical process design

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ABSTRACT

Inherent safety indices have been suggested to choose between alternative process and chemical reaction routes in conceptual chemical process design. The indices are relative ranking methods that add up parameters without considering the difference in the magnitude of the hazard, complexity of the procedure, or expert opinion. We propose an improved framework based on fuzzy logic using chemical properties, process data, and chemical accident databases. The proposed methodology is applied to the methyl methacrylate (MMA) process as a case study. The results are compared with existing methods and experts' rankings by using three risk-rules, which are related to the experts' opinions and the tendency of decision makers. The risk-standard rule showed same results to that of the expert's scoring, while the ranking results are slightly different based on risk-easy and risk-hard rules. This methodology can facilitate the ranking of alternatives for decision making in the preliminary design stage.

1. Introduction

The development of sustainable chemical processes is one of the core activities in the production of chemical materials in chemical process industries. In particular, process design and synthesis are essential engineering activities based on mathematics, basic science, engineering science, economics, safety, reliability, and social considerations, among many other factors. Nowadays, process design is more important than ever because of the increase in process complexity, handling of critical operation conditions, and treatment of toxic materials (Sugiyama et al., 2008). However, complicated processes, hazardous materials, and operating conditions prevent sustainable process design.

Several chemical accidents have occurred because of design faults or the overlooking of hazards at an early stage in process design. The Health and Safety Executive examined 34 accidents that were the direct result of control and safety system failures in various different industries. They found that 15% of accidents were caused by faulty design and implementation (Jang et al., 2009). To reduce these accidents, the inherent safety of the process design must be considered from the conceptual design stage to construction to enable the installation of inherently safer features (Bollinger et al., 1996). In this manner, inherent safety plays an important role in the design of safer processes, identifying sustainability based on materials, the handling of critical operation conditions, the operation of large inventories, and the management of process complexity in the process design and plant life cycle (Khan and Amyotte, 2003).

Several inherent safety indices have been suggested and considered to help decide process and chemistry reaction routes from alternative processes in the chemistry design phase and conceptual design phase. However, detailed process information is needed to evaluate the chemical processes, and supplemental characteristics are required to evaluate the inherent safety characteristics. Moreover, the inherent safety indices are relative ranking methods, achieved by adding parameters without any considerations of the differences in the magnitude of the hazards, the complexity of the procedure, or expert experience and opinion. To improve the existing inherent safety indices, a new framework and method for inherent safety assessment to enhance the sustainability in conceptual chemical process design is presented. To validate our proposed method, a methyl methacrylate (MMA) production process was evaluated, and the evaluation results are compared with other leading methods.

2. Development of inherent safety indices

By the early 1990's, several existing evaluation methods for process

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safety had been developed, such as the Dow and Mond indices and HAZOP studies. Unfortunately, these are not directly suitable as analysis tools for preliminary process design. In particular, most of these methods require excessively detailed information and expert knowledge. Thus, it is difficult to apply these complicated hazard assessment methods to computer-aided systems such as process simulation and optimization (Rahman et al., 2005). Consequently, several researchers have proposed tools for inherent safety evaluation in the early process design stage.

The Hazard Identification and Ranking (HIRA) was developed by Khan and Abbasi (1998). HIRA is an index to overcome some of the limitations of the Dow Fire & Explosion Index (F&EI) because the material factor is considered as independent of the operating conditions and it depends more on expert opinions than on the system properties. The structure of the HIRA index has had additional impact on the I2SI index (Khan and Amyotte, 2004), which is called an integrated index because the procedure considers the life cycle of the process with economic evaluation and hazard potential identification for each option. Even though I2SI index can estimate the cost for inherent safety, it needs a lot of assumptions in the preliminary design stage and tends to be simplified in the detailed design stage. The proposed method in this study evaluates semi-quantitatively the inherent safety and applies an acceptance tendency of a decision maker about risk to the inherent safety of a system.

Another application of the HIRA index was the Quantitative Integrated Inherent Safety Design index (Q2ISD) (Rusli et al., 2013), which identifies potential Inherent Safety Design (ISD) option by estimating the potential damage and evaluating hazard conflicts that could be transferred to other parts of the process after Inherent Safety (IS) principles are considered. A similar approach was used for the Quantitative Inherent Safety Assessment by Key Performance Indicators (KPIs) by Tugnoli et al. (2009). This index proposes a procedure for identifying the inherent hazards and a method to quantify the safety performance by means of consequences. The index can only be used in the detailed design stage of the process. The proposed method in this study can be also used in the detailed design stage of the lifecycle of a whole process design procedure. An index for inherent safety was first developed by Heikkila (2000), who labeled it as Inherent Safety Index (ISI). This index was partly based on the PIIS index of Edwards and Lawrence (1993). This index quantifies or scores the factors that define the principles of inherent safety, namely minimization, moderation, substitution and simplification. This was further enhanced into the Enhanced Inherent Safety Index (EISI), the i-Safe Index (Edwards and Lawrence, 1993), the Comprehensive Inherent Safety Index (Gangadharan et al., 2013), and Inherent Safety Index Module (ISIM) (Leong and Shariff, 2008).

Another approach was developed by using fuzzy indices. A pioneer work in this area was done by Gentile et al. (2003). The use of fuzzy logic is helpful modeling uncertainty and subjectivities implied in evaluation of certain variables and it is helpful for combining quantitative data with qualitative information. It converts linguistic variables into fuzzy ranking of the chemical for each type of hazard. Chemical properties and plant layout are some of the factors taken into account by this index. To improve the traditional risk matrix, the fuzzy risk matrix was introduced by Markowski and Mannan (2008). In this method, all variables of the risk matrix were defined based on fuzzy set and appropriate membership function. Application of fuzzy set theory to handle the uncertainties associated with bow-tie was discussed by Markowski et al. (2009), Markowski and Kotynia (2011). Fuzzy logic has been used in several research areas including process safety analysis (Jang, 2012; Hong et al., 2016; Markowski et al., 2010).

Another set of indices is related to life-cycle. The indices quantify the risk and hazards because of various parts of the product life-cycle including processing, storage and transportation and their effect to society and the environment (Al-Sharrah et al., 2007; Khan et al., 2004a,b; Reniers et al., 2012). For instance, the Life Cycle (LinX) (Khan et al., 2004a,b) assesses various properties of the life cycle of a technology such as environment, health and safety as well as technological costs and socio-political aspects. The parameters have been grouped intuitively into sub-indices, and a weighted average is used to give a single ranking. However, the ranking is based solely on expert opinion. Several indices have also been developed specifically for transportation (Bonvicini et al., 1998; Cafiso et al., 2007; Scott, 1998) and the waste disposal of chemicals (Musee et al., 2006).

Various safety approaches for in offshore oil and gas activities are studied by several researchers. The safety approaches have developed fire consequence model for quantitative risk assessment (Pula et al., 2005), a method for analyzing human error risk (Abbassi et al., 2015; Deacon et al., 2010; DiMattia et al., 2005), a conceptual accident model (Kujath et al., 2010), a way to assess emergency evacuation behavior using a Bayesian Network approach (Musharraf et al., 2016), a fire impact assessment using computational fluid dynamics (CFD) (Baalisampang et al., 2017), and so on (Khan and Amyotte, 2002). In addition to that, safety challenges in harsh environments were discussed in an industrial workshop on safety and integrity management of operations in harsh environments, which was organized by the safety and risk engineering group at Memorial University of Newfoundland (Khan et al., 2015a). The inherent safety approach is also considered as the best option for hazard/risk management in offshore oil and gas activities (Khan et al., 2004a,b; Xin et al., 2016, 2015). For example, Layout optimization of a floating liquefied natural gas facility was studied by using inherent safety principles (Xin et al., 2016). Layout plays a key role in the FLNG facility. It decides area and equipment arrangements and influences accident magnitude and propagation routes of hazards. Therefore, an optimal layout can greatly enhance plant safety and effectively mitigate hazards. That work shows a new way of thinking that sets safety as a starting point and tries to balance costs of safety measures with unexpected extra costs brought by potential risks. In addition, other existing safety-related indices are discussed in the review paper. (Khan et al., 2015b; Roy et al., 2016; Srinivasan and Natarajan, 2012).

In this study, the evaluation results obtained from the representative indices including PIIS, ISI, and i-Safe, and expert evaluations are compared with those obtained using the proposed method. In addition, the general properties of the indices are discussed.

3. Inherent safety performance indices (ISPI)

The inherent safety performance indices (ISPI) is proposed based on the fuzzy logic methods (IF-THEN rules) integrated with a process simulator, as shown in Fig. 1. First, the essential chemical and process properties are selected and categorized. Then, IF-THEN rules are written, based on expert experience and opinions, in Matlab. Finally, the ISPI is applied to evaluate the inherent safety using calculated property parameters in a process simulator (Aspen Plus).

3.1. Concept of the proposed method

In this section, we describe how to select and form the inherent safety performance index (ISPI). The whole procedure to define the ISPI is illustrated in Fig. 2. The proposed method is focused on the

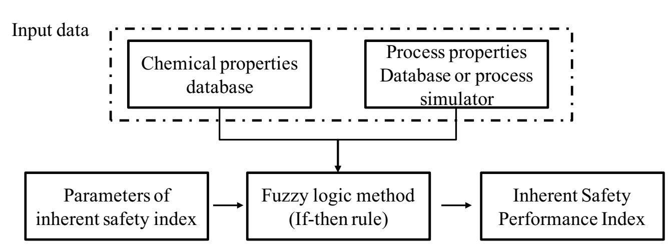

Fig. 1. The procedure for the configuration and operation of the proposed method.