Chemical Engineering Science 119 (2014) 218–229

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

New simple indices for risk assessment and hazards reduction at the conceptual design stage of a chemical process

Mohammad Hossein Ordouei [a,*], Ali Elkamel [a], Ghanima Al-Sharrah [b]

[a] Department of Chemical Engineering, University of Waterloo, 200 University Avenue West Waterloo, Ontario, Canada N2L 3G1
[b] Department of Chemical Engineering, Kuwait University, P.O. Box 5969, Safat, Kuwait

HIGHLIGHTS

- Risk indices based on chemical hazards and accident frequency are proposed.
- The indices can be used at conceptual design phase to address risks to process safety.
- Linear dependency of indices on hazard mass fraction conceptualizes inherent safety.
- The risk indices make it possible to evaluate risks independently from process size.
- Indices assess risks at minimum available data as screening tool among design array.

ARTICLE INFO

Article history:
Received 8 February 2014
Received in revised form
4 July 2014
Accepted 31 July 2014
Available online 21 August 2014

Keywords:
Inherently safer process design
Process simulation
Risk reduction
Conceptual design
Risk indices
Environmental Impact

ABSTRACT

Inherent safety has been of great interest to regulators, process designers and investors. The idea behind this is that a process design is more economic when it is inherently safer. Inherent safety is known as the safety intrinsic to a process; the spirit of which is to mitigate hazards within the process. It is also possible to achieve inherently safer design by diminishing the hazards in multi-component streams during process design. Hazards reduction during the design phase is a challenging task. A decrease in hazards in a process design not only improves process safety, but also protects the environment from potential impacts of the process. Current methodologies for risk assessment at the conceptual design stage of a chemical process need detailed process data, which is usually unavailable at such a phase. This paper presents simple new indices that require minimum data for risk evaluation of chemical processes at the conceptual design phase. The indices are applied to a hydrogenation case study to choose inherently safer designs among different alternatives. As an important result, total capacity of a process among other design array does not suffice for decision making unless the mass fraction of hazards in product streams are appreciably low.

1. Introduction

An accident in a chemical manufacturing plant is not only harmful to the plant; it can also be an irreparable spoil for the reputation of the licensing company who has designed the chemical process. This fact reveals that it is imperative to alleviate possible risks to process safety during the design phase. The tie between process design and the risk to process safety is not new; any kinds of design modifications and/or the development of operating instructions result in risk reduction within the process plant; e.g. purification of raw material, centralization of hazardous chemicals in safe containers or bags and transformation of the hazardous chemicals to benign materials (Carson and Mumford, 2002). There are several qualitative and quantitative methods to estimate the risks associated with a chemical process; however, few of them can be used in conceptual design.

Chemicals, in general, are the main source of fire, explosion, toxicity and corrosion hazards. About two third of impacts were initiated mainly by explosion compared to fire (Lees, 1996); however, toxicity is more influential on the number of affected people compared to fire and explosion (Belke, 2000). Thus, it is vital to pay close attention to the chemical toxicity for the risk assessment during the primitive step of process design, especially in the absence of detailed information about the process.

Hazard is an intrinsic chemical or physical property of a material or a system or a process, which can be detrimental to human, plant, equipment, and environment. Hazard and risk have two distinctive concepts (Canadian Centre for Occupational Health

* Corresponding author. Tel.: +1 519 888 4567x31634; fax: +1 519 888 4347.
E-mail address: mhordoue@uwaterloo.ca (M.H. Ordouei).

http://dx.doi.org/10.1016/j.ces.2014.07.063
0009-2509/

and Safety, 2009). A "hazard" refers to the potential of negative consequences on personnel's health or company's equipment and property, while a "risk" is defined as the probability of the hazard, which results in adverse effects on the human, the property or the equipment. Hence, the risk is generally a function of two factors; frequency and consequences:

$$\text{Risk Assessment} = f(\text{Frequency, Consequences}) \quad (1)$$

This relationship has persuaded Marhavilas et al. (2011) to develop a model called decision matrix risk assessment (DMRA). It is also widely being used by other researchers and engineers (Reniers et al., 2005; Woodruff, 2005; Henselwood and Phillips, 2006; Marhavilas and Koulouriotis, 2008).

Researchers have made several attempts to provide simple methodologies for the evaluation of potential risk to a process safety. A simple risk index is a mathematical model to be employed in the primitive stage of planning in chemical plants, easily applicable in process plants, include industrial experience and require general plant (Al-Sharrah et al., 2007).

The review of such methodologies is out of the scope of this paper; examples include (but not limited to) STEP, HAZOP, What-If Analysis, PRA, Checklist Analysis, SA, TA, FTA, DMRA, The Measure of Societal Risk (Marhavilas et al., 2011).

A table of the above most commonly used methods, their formulations, parameters of risk estimation, advantages, applications and disadvantages is provided in Appendix A. These risk analysis methods have one or a combination of several disadvantages such as qualitative, comprehensive, time consuming, dependant on the quality of either of training data collectors receive or experience of safety/production managers, require detailed process data, which is unavailable at the early stage of process design to name a few. Detailed discussions about the available methodologies have been made by Koller et al. (2001), Tixier et al. (2002), Al-Sharrah et al. (2007) and Marhavilas et al. (2011).

Koller et al. (2001) have reviewed and classified the major characteristics of 13 index methods and made the following recommendations to be applied at the early design stage:

- The combination of different methods.
- Possible risk evaluation in lack of detailed process data; e.g. equipment and plant.
- The advantage of history of previous incidents and accidents are constructive.

Tixier et al. (2002) have identified 62 safety risk analysis methods in industrial plants and pointed out the lack of human risk analysis in classical risk evaluations as the disadvantage of most of these methodologies.

Al-Sharrah et al. (2007) have implemented the above-mentioned shortcomings to their risk index for use in petrochemical planning as follows:

$$K = Freq \times Haz \times Inv \times Size \quad (2)$$

The index (K) expresses the risks to human life in maximum affected people per year (including fatalities, injuries and people hospitalized) if the plant chemical inventory were released in an accident. *Freq* is the frequency of accidents in number of accidents per process per year, *Haz* stands for hazard effects in number of people affected per ton of chemical released, *Inv* designates the inventory in tons of chemical released per accident, and the term *Size* is the number of major processes in plant, which is most often equal to three since chemical plants are usually divided into three main process sections; reaction, purification and finished product storage facilities. It is important to note that most plants have purification and storage facilities for both reactants and products and they both share the reaction section.

Marhavilas et al. (2011) have classified the main risk assessment methods into three main categories: qualitative, quantitative and hybrid techniques and concluded that current methods have not been fully shared. Hence, the researchers encounter issues such as duplication and cohesion from one field to another.

The risk index given by Eq. (2) has been embedded in a multi-objective tool for strategic planning of the petrochemical industry (Al-Sharrah et al., 2006). It was recently used as part of sustainability indicator for decision-making and optimization in process plants (Al-Sharrah et al., 2010).

2. Inherent safer design

Eq. (1) represents the dependency of the risk on frequency (probability, likelihood) and consequences. The fundamental question is which process should a process engineer opt for, when two processes with the same potential risks are concerned? The process, which has higher likelihood of accidents but lower consequences? Or the one, which has lower likelihood of accidents but severe consequences?

Engineering design is based on codes and standards, which provide consistent tools for material selection, reliable procedures for fabrication, tests and installation of piping and equipment used for handling of hazardous and non-hazardous chemicals and facilities. Unlike hazardous materials, which escalate further costs due to safety reasons, the codes allow the engineers to use mild materials when benign chemicals (meaning low consequences) are concerned resulting in cheaper expenditure. This is the core of the inherent safety in a chemical process; i.e. hazards alleviation instead of employing protective devices (Heikkilä, 1999). Consequently, the question of the severity and the likelihood of an accident can be addressed when hazards have been identified.

Inherently safer design (ISD) is highly supported by the availability of simple indices that can be used at early stages of design. ISD is an approach to address the risks of hazardous chemicals to human, environment and process plant during design and manufacturing phases of a process (Hendershot, 2011a). The term ISD was first introduced in the 1970s after the big disaster in Flixborough, UK, in 1974; however, the concept of inherent safer design (ISD) is not new. It has been used since Stone Age when cave inhabitants decided to move up to a higher level of the cave to diminish the risk of flood, while they could reduce the risk by either of dike (engineering control) and monitoring the level of river (administrative control).

Today, more researchers and engineers are becoming familiar with ISD through new publications and training such as the relevant course provided by AIChE:

https://www.aiche.org/ccps/resources/education/courses/ch800/inherently-safer-design

Together with engineering and administrative controls, ISD is able to manage the risks of a process efficiently. There are four strategies to design an inherently safer process (CCCP, 2009):

1. Substitution of hazardous chemicals with benign materials.
2. Minimization of hazardous materials.
3. Moderating the process by dilution, refrigeration etc.
4. Simplification of operation by reducing the potential errors such as using interlocking commands for process control equipment.

It is now possible to replace toxic chemicals in off-shore oil and gas facilities during conceptual design in order to design an inherently safer process at optimum cost and minimum acceptable risk (Khan and Amyotte, 2002). The concept of inherent risk assessment has been used for the integration of risk quantification