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Risk-based process plant design considering inherent safety

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ABSTRACT

An inherently safer approach is becoming a key parameter of process and plant design. However, a lack of established guidelines and methods hinders most industries from utilizing inherent safety concepts to a full extent. This paper presents a risk-based design decision-making tool considering inherent safety. The tool is called the Risk-based Inherent Safety Index (RISI). The proposed indexing approach is an extension of the Integrated Inherent Safety Index (I2SI) earlier developed by Khan and Amyotte (2004, 2005). The RISI incorporates both consequence and probability of accident occurrence reduction through application of inherently safer design principles throughout the process design life cycle. Unlike other available dimensionless index-based matrices, risk components of the proposed indexing approach are expressed in terms of SI units. The RISI is applicable at different stages of the process design life cycle. Analytical and subjective equations assess the damage potential of major process accidents: fire, explosion and toxic release. The explosion accident scenario is studied separately in terms of vapor/gas explosion and dust explosion. The decision-making potential based on the quantitative results of the methodology is demonstrated by evaluating alternatives for biodiesel production.

1. Introduction

Traditional technical and economic aspects are not the only consideration for product and process plant design. Different aspects such as sustainability, environment, health and safety have recently gained significant attention in process plant design and development (Banimostafa et al., 2012; Ouattara et al., 2012; Tugnoli et al., 2012). The application of inherently safer design (ISD) principles into design and utilization of inherent safety as a decision-making tool during the process life cycle has been identified as a reliable and better technique to produce a safer, sustainable and economically viable process plant. The fundamental concept of inherent safety was first formulated by Professor Trevor Kletz and since then, its advantages and applications have been extensively discussed (Kletz, 1978, 1984, 1991; Kletz and Amyotte, 2010). Further, assessment of inherent safety remains an active topic of interest in the process safety design community.

Index-based metrics have been developed as indicators to assess the level of inherent safety of a process system. Hence safety–critical decisions are made based on these indicators during various stages of the process design life cycle. The properties, limitations and applicability of existing index-based inherent safety assessment metrics and models are broadly discussed in Khan et al. (2003), Rahman et al. (2005) and Srinivasan and Natarajan (2012).

The present work is a continuation of earlier efforts to develop an effective and accessible method to analyze and implement inherent safety throughout the process design life cycle. In this paper, a risk-based decision making tool considering inherent safety is developed to choose an optimum design. The tool is called the Risk-based Inherent Safety Index (RISI). The RISI is comprised of two distinct risk elements: base design risk (*RiskBD*) and inherent safety risk (*ISRisk*). Unlike other available dimensionless index-based matrices, both risk calculations in the RISI methodology are expressed in terms of units. In the present work SI units are used. The RISI aims to improve design by applying inherently safer design principles into different stages of the process design life cycle.

This paper is organized into two main sections: methodology description, and testing and verification using a case study. Several important equations and derivations are developed as part of the methodology and are listed in the Appendices accompanying the text.

2. Process design life cycle

Process design is a complex activity that is carried out in different stages over a period of time. Design at each stage involves

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Nomenclature

V	volume of the vapor cloud (m^3)
ΔH_C	heat of combustion (kJ/kg)
ρ	density of the flammable material (kg/m^3)
OP	operating pressure of the process unit (kPa)
γ	specific heat ratio
VP	vapor pressure (kPa)
β_C	compressibility (kPa^{-1})
mm	molar mass of the chemical (g/mol)
ΔH_f	enthalpy of the reaction (kJ/mol)
C	explosive dust concentration (kg/m^3)
V_C	volume of the confinement (m^3)
P_{max}	maximum explosion pressure (kPa)
P_{atm}	atmospheric pressure (kPa)
γ_a	heat capacity ratio of air at maximum explosion temperature
MIT	minimum ignition temperature (°C)
D	diameter of the pool (m)
u	wind velocity at a 10 m height (m/s)
u_c	characteristics velocity (m/s)
g	gravitational acceleration (m/s^2)
m'	burning rate (kg/m^2 s)
ρ_a	density of air (kg/m^3)
V_U	volume occupied by the units in 30 m radius (m^3)
M	mass of the flammable substances (kg)
S	burning speed (/s); $s = 2.3\ U_w$
U_w	wind speed at the elevation of the closed vertical center of mass (m/s)
CD	cloud depth (m)
T_0	temperature at the source (°C)
P_0	pressure at the source (kg/cm^2)
A	area of the source (m^2)
f_v	fraction of the liquid that will flash; $f_v = \frac{C_P}{H_V}(T_s - T_b)$
C_P	average heat capacity of the liquid (J/kg °C)
H_V	heat of vaporization (J/kg)
T_b	normal boiling point (°C)
T_s	operating temperature (°C)
ρ_L	density of the liquid release (kg/m^3)
P_g	pressure inside the vessel (kPa)
A_P	pool area (m^2)
MW	molecular weight
T_P	characteristics pool temperature (°C)
h_L	height of the liquid above the release point (m)
K	constant ($K = 3.14$)

assessing, analyzing and evaluating design alternatives to enhance safety along with other objectives such as economics, quality, productivity, energy conservation and pollution prevention. The process design life cycle represents this evolution over time (Fig. 1). Researchers and regulatory bodies have classified stages for the process design life cycle in different ways as relevant to their own studies (CCPS, 2009; Palaniappan et al., 2002a; Mannan, 2005; Hurme and Rahman, 2005; Tugnoli et al., 2008). In the present work, the process design life cycle is divided into five stages and they are considered as key design decision-making points. These are (as shown in Fig. 1): (1) conceptual design, (2) process selection and design (3) detailed engineering design and commissioning (4) operation and modification and (5) decommissioning.

Conceptual design begins with researching an idea for a new product or process. Research is carried out to determine the technical, economic and safety feasibility. If the product is practical and feasible, conceptual design begins. The main purpose of conceptual design is to study the process chemistry and to evaluate available chemical synthesis routes. The chemical reactions involved, raw materials, intermediate and by-products, storage, transportation and waste treatment associated with each synthesis route are further studied.

Once conceptual design efforts lead to configuration of the process chemistry and synthesis routes, a process flow-sheet is developed. This stage is called the process selection and design stage. Information on desired product rates, product purity, heat transfer fluids, solvents, catalysts, control and operational methods gathered from conceptual design, laboratory and pilot scale trials and knowledge of the existing process are used to develop the base design flow-sheet. During this stage, key decisions on selection of unit operations, conversion factors, process parameters such as temperature, flow rate, pressure, and selection of solvents and catalysts are taken into consideration.

Once the process flow-sheet is developed, further studies are carried out to improve operating conditions, optimize product yields and energy usage, improve product quality, and investigate the need for recycling by using information from process engineering design principles, computer-aided simulations and expert knowledge. The detailed engineering design stage focuses primarily on detailed piping and instrumentation design, electrical and insulation designs, process control and automation, utilities and support equipment and safety instrumented systems. During this stage, a design and commissioning team along with engineering, procurement and construction management (EPCM) contractors will carry out construction and plant commissioning.

Finally the operational team will be handed over the plant for start-up of operations. There is a belief that the applicability of inherent safety strategies is significantly limited during the operation and modification stage. During this stage, which is the longest stage of the process design life cycle, many changes in operation, personnel, maintenance and equipment will likely occur. CCPS (2009) highlighted two main tasks for consideration of inherent

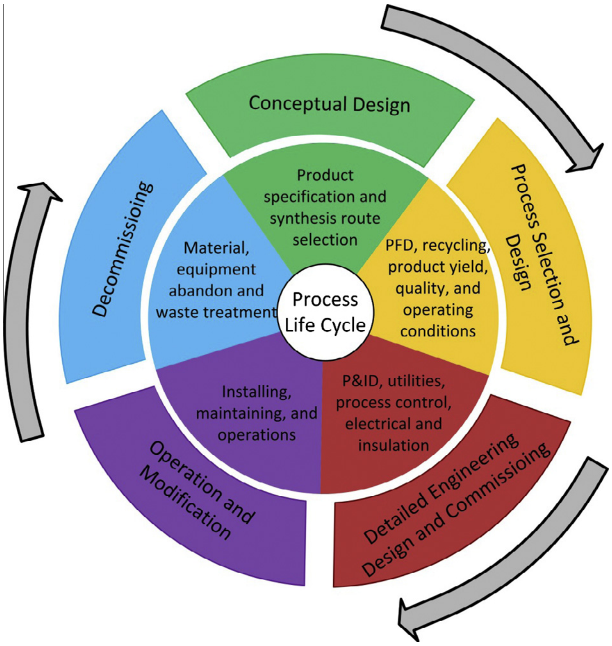

Fig. 1. Classification of stages of the proposed process design life cycle.