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Analysis of explosion accidents with heat recirculation dryers and their inherent safety improvement

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ABSTRACT

The explosion accidents occurred at the drying workshops in China were found mostly to be caused by explosive gas mixtures formed in drying chambers. During the heat recirculation drying of surface coatings, solvent vapors are released forming explosive mixtures when the lower explosion limit of their concentration in air is reached. The analysis of exploded dryers and the numerical modeling served their inherent safety improvement ideas presented in this research. The improvement in heat recirculation drying safety was achieved with evacuation and oxygen concentration control using nitrogen. The drying gas double circuits at inlet and outlet of the drying chamber were installed to maintain an inert gas minor excess pressure (≤0.1 MPa) in the drying chamber. Oxygen concentration thus did not exceed 7.0 vol %. The drying time was substantially shortened, and the energy consumption was thus reduced for 67%. The present study provides an explosion prevention strategy with regard to inherent safety of heat recirculation dryers in design and operation.

1. Introduction

Heat recirculation drying is widely used in chemical, pharmaceutical, painting and other production due to its high energy efficiency and an even heat distribution. However, the surface coatings applied in chemical production often contain flammable and volatile organic solvents able to accumulate in drying chambers. An ignition source, for example, static electric spark may initiate an explosion when the concentration of flammable solvent in air reaches the boundary of the limit of explosion. In recent years, the accidents with solvent vapors explosions in heat recirculation dryers took place in China, sometimes causing casualties and lost property.

Fig. 1 shows the scene of accident with the heat recirculation drying equipment exploded in the drying room of a company in Guangzhou, China, on August 13, 2011. The accident occurred during the drying process of work pieces covered with coatings. At the instant of explosion, not only the chamber lid burst open, but the windows in the room were shattered. This accident claimed serious injuries of two workers and the direct economic loss of more than 526,000 US dollars. After the primary investigation of the case, the cause of the accident was established to be an explosive vapor mixture formed with high concentration of styrene vapors in air. The mixture was ignited by the overly high operation temperature during the drying process.

To prevent accidents at the heat recirculation drying processes, the Standardization Administration of China (SAC) implemented a national standard GB14443-2007 “Safety code for painting - safety rules for paint drying oven”. The standard requires the frequent fresh air supply and the flue gas discharge applied in drying compartments to control the combustible gas concentration below 25% of the lower explosion limit (LEL). The substantial fresh air feed, however, results in uneven drying and a waste of heat bringing the safety requirement in conflict with the efficient drying. Besides, the risk of fire and explosion remains in case of the ventilation equipment malfunction.

Different from the standard safety approach given in the GB14443-2007, the inherent safety design is a technique of the risk reduction at the source of process design and development. The inherent safety design applies comprehensive measures such as reducing or eliminating of hazardous materials and errors of operation. The potentially dangerous materials are substituted with non-hazardous ones in order to avoid the risk of accident during the product manufacture, shipping or use.

There are four key principles of inherent safety design (Amyotte et al., 2009):

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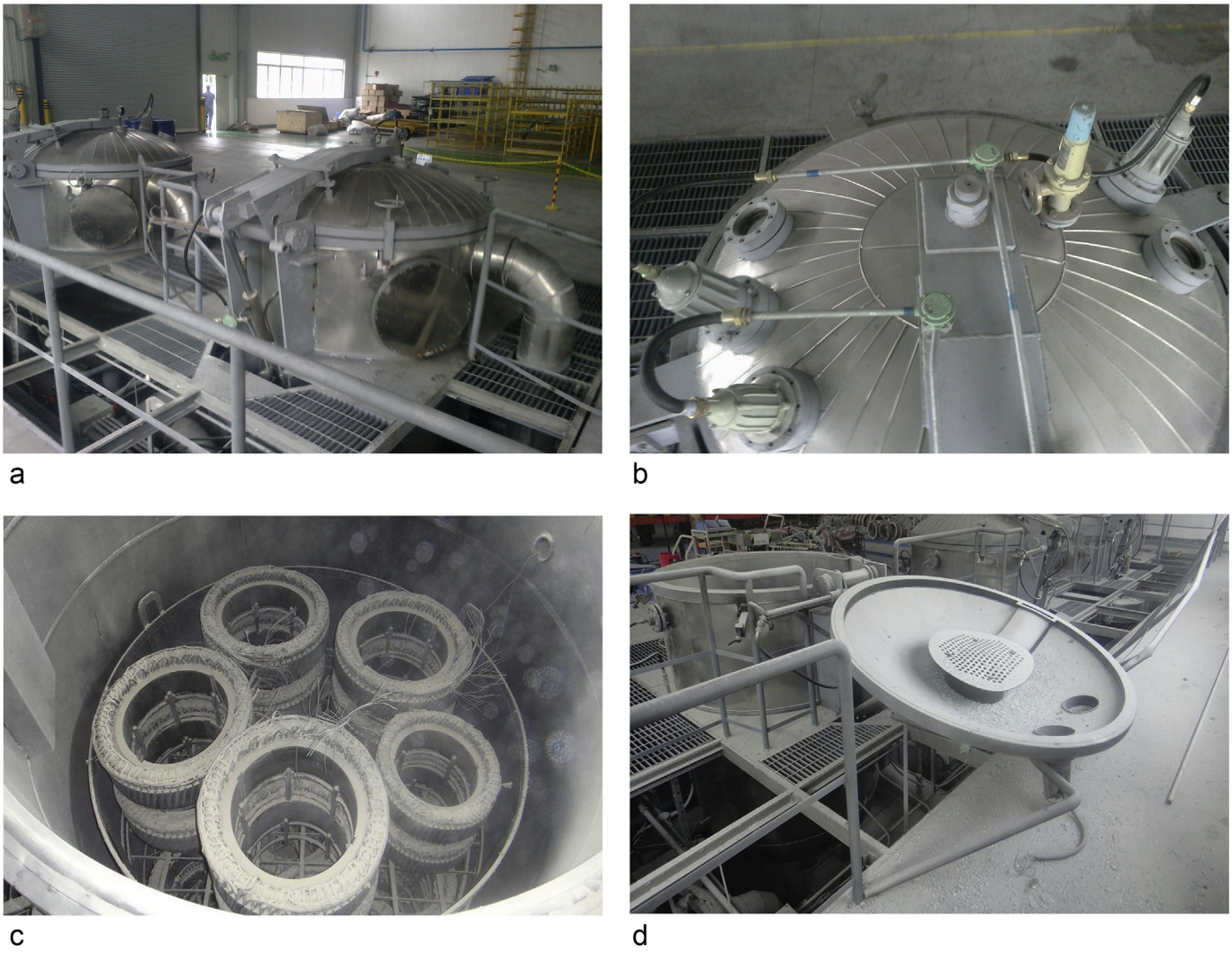

Fig. 1. The scene of accident with the exploded drying equipment. a) Drying chamber destroyed by the explosion. b) Top view of the drying chamber. c) Machine windings after the explosion. d) Chamber lid blew open by the explosion.

(1) Minimization of the hazardous materials use or, when unavoidable, performing the hazard minimizing procedures;
(2) Substitution of high-risk materials or processes with the low-risk ones;
(3) Moderation: applying hazardous materials under low-risk conditions, i.e. adopting a safer operating conditions or methods for hazardous materials storage and transportation; using hazardous materials in their least hazardous forms.
(4) Simplification: designing of simple processes, equipment or systems to reduce the potential of human errors.

These principles are applied in the practical design, such as adopting a new process avoiding the hazardous raw materials, reducing the severity of process conditions, increasing safety and reliability of the equipment, or reducing the quantity of hazardous media in the process. A number of studies on inherent safety design has been conducted in recent years. Goraya et al. (2004) proved the benefits of applying the principles of inherent safety design in accidents prevention in the case studies. Hendershot et al. (2006) extended the inherent safety design to the existing equipment modification. Carvalho et al. (2009) carried out the sustainable design alternatives research on batch or continuous processes approaching from the inherent safety point of view.

After several years of research on the evaluation of inherent safety, a few groups of scholars proposed quantification criteria of the risk assessment. These include the Prototype Index of Inherent Safety (PIIS) (Edwards and Lawrence, 1993), the Inherent Safety Index (ISI) (Heikkilä et al., 1996), the Safety, Health and Environment Index (SHE) (Koller et al., 2000), the i-Safe Index (Palaniappan et al., 2002), the Fuzzy Based - Inherent Safety Index (Gentile et al., 2003), the Integrated Inherent Safety Index (I2SI) (Khan and Amyotte, 2004), and the Inherent Benign-ness Indicators (IBI) (Srinivasan and Nhan, 2008).

Nonlinear numerical models are widely used for analyzing phenomena difficult in performing field experiments for their high complexity or applied restrictions, e.g. technical, economical, or environmental conditions. A number of successful applications of nonlinear numerical models was described in Valipour's previous research (2012a, b; Valipour et al., 2013; Valipour, 2014, 2015a, 2015b). Additionally, based on computational fluid dynamics (CFD) model, Siddiqui et al. (2012) performed a simulation of the accidental release of chlorine gas with sustained, small, undetected leak in an industrial indoor environment and analyzed its spreading pattern and risk mitigation. Cheng et al. (2016) presented a detailed three-dimensional mathematical description and a simplified unidimensional model for the numerical simulation of