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Environment & Safety Risk Analysis of Storage Tank Accidents Based on Vulnerability, Process Management and Emergency Management

Xiaoqiang Kong[a,b], Dongfeng Zhao[a,*], Su Hu[c]

[a] College of Chemical Engineering, China University of Petroleum (East China), Qingdao 257061, China
[b] SINOPEC Safety Supervision Department, Beijing 100728, China
[c] SINOPEC Yangzi Petrochemical Company Ltd., Nanjing 210048, China
zhaodf@vip.sina.com

This paper aims to assess the risks of storage tank accidents and identify proper countermeasures. For these purposes, the causes and scope of tank accidents were discussed, and the scope of risk assessment was expanded from accident possibility and consequence severity to the hazard degree and vulnerability of the hazard-affected bodies. Then, the risk of storage tank accidents was evaluated from three aspects: accident possibility, hazard degree and vulnerability. Then, several risk control measures were put forward with the aim to control the hazard sources, block the propagation path and decrease vulnerability. After that, the proposed measures were validated through a case study on an oil tank farm of a coastal refinery in China. Specifically, a full-surface fire was simulated on one of the oil tanks in the tank farm, the effects of the fire on the adjacent tanks and pipe rack were observed, and several countermeasures were proposed to minimize the hazards. The research findings shed new light on the understanding and prevention of storage tank accidents.

1. Introduction

Storage tanks provide an important storage medium of crude oil and oil products, which is indispensable to oil and petrochemical industries. Over the years, storage tanks have been widely applied in ports, wharfs, warehouses and refineries. The application intensity and scale are continuously on the rise. By 2020, the capacity of China's national strategic oil reserve is estimated to be approximately 85 million tons (Chen, 2012), fuelling a huge demand for large storage tanks.

Storage tanks have the potential to cause major hazards, because of their dangerous features, huge volume and close layout. Recent years have seen a series of tank accidents across China, such as the tank explosion at CNPC Lanzhou Petrochemical Company, the flash explosion at CNPC Dalian Petrochemical Company and fire and explosion in Rizhao. These accidents are a stark reminder of the importance of hazard control in the design, construction, operation and maintenance of storage tanks. Much research has been done on the hazard control of storage tanks. For instance, K.P. Bloch analysed the explosion of a spent caustic tank and reduced the risk of the failure in process safety management (PSM) (Bloch and Wurst, 2010). J. Sakamoto estimated the scale of gasoline tank fires with a hazard assessment tool and adopted ANSYS to predict temperature and stress based on temperature distribution (Sakamoto et al., 2016).

Inspired by the previous research, this paper integrates theoretical analysis, field research and numerical simulation to discover feasible measures for reducing the risk of tank accidents.

2. Preliminary Analysis

2.1 Cause Analysis

After analysing 83 storage tank fire and explosion accidents (Jiang et al., 2016), 94% of the storage tanks had internal fixed/floating roof or the external floating roof; 59% of the storage tanks contained such materials as gasoline, crude oil and naphtha; 60.4% of these accidents were caused by ignition sources like lighting,

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construction flame and electrostatic spark. In general, tank accidents are premised by oil and gas leakage of the tanks and the ancillary facilities (Bariha et al., 2016). However, the leakage can't induce storage tank fire or explosion without an ignition source or sufficient energy. According to the accident development process (Figure 1), a tank accident has an impact on personnel, equipment, materials and environment. All these factors being affected are collectively known as hazard-affected bodies (Khakzad et al., 2016).

The materials leaked from the storage tanks and the ancillary facilities may cause pollution to the environment (e.g. the release of volatile organic compounds) and incur economic losses to the enterprises. If the materials are toxic, the leakage would also lead to human poisoning and tarnish the reputation of the enterprises; If the materials are flammable, fire and explosion accidents would occur under the condition of sufficient energy. The resulting blast waves and thermal radiation may cause personal casualties, Infrastructure damages, property loss, environmental impact (including environmental disruption and negative social repercussions).

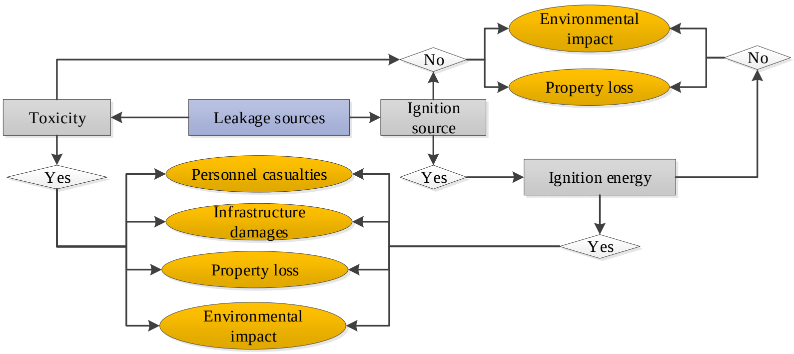

Figure 1: Accident development

2.2 Scope analysis

The risk of tank accidents is affected by various factors, including but not limited to the amount of leaked materials, energy of initiation sources and the types of hazard-affected bodies. Even if the storage tanks comply with relevant laws and regulations, tank accidents still occur from time to time owing to hardware problems, maloperations and management flaws. Hence, storage tanks must be subjected to risk analysis in addition to compliance analysis. Operation accidents (e.g. falling and electric shock) and process safety accidents (e.g. fire, explosion, poisoning and suffocation) may occur during the construction, operation and maintenance of storage tanks. These accidents are attributable to various defects that are difficult to eliminate completely. The risk degree of tank accidents varies with the time, leak materials and operation conditions. Traditionally, the risk degree is assessed against the possibility of accidents and the consequence severity caused by the hazards. Considering the close correlation between the damages on hazard-affected bodies and the exposure, sensitivity, coping capacity and recovery capacity, it is necessary to expand the scope of risk assessment from accident possibility and consequence severity to the hazard degree and vulnerability of the hazard-affected bodies.

3. Risk Analysis

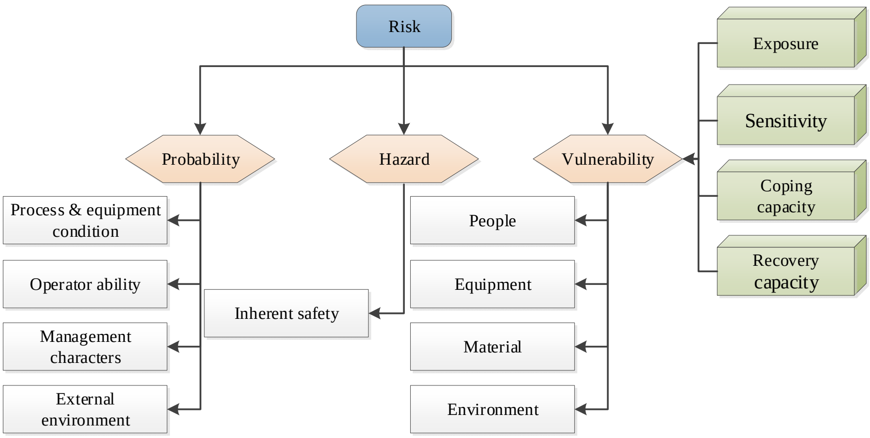

Figure 2: Block diagram of risk

The risk of tank accidents is illustrated in the block diagram of Figure 2 considering the accident possibility, hazard degree caused by the hazards and the vulnerability of the hazard-affected bodies.

3.1 Accident possibility

To identify the possibility of tank accidents, the first step is to determine the potential leakage sources, such as tanks, pipes, breather valves, safety valves, coupling hoses, etc. The possible causes of leakage are associated with either hardware or software. The hardware causes are further divided into equipment reliability and external environment, while the software causes include operator quality and management level.

Specifically, the equipment reliability mainly concerns conveying, storage, discharge and relief systems; external environment refers to the impacts of other operations (e.g. hot work and temporary power operation) on storage tanks; operator quality is demonstrated by skills, professionalism and mental/physical health; management level is manifested as post responsibility, safety management, training & inspection and operation approval.

3.2 Hazard degree

The hazard degree depends on the inherent safety of leaked materials. The inherent safety of leaked materials is reflected by the process data, natural environment and the dangerous features of the materials (e.g. flash point, explosion limit and toxicity) and so on. The operating conditions are extreme, the natural environment is severe, more dangerous and larger amount of the material is, more serious the hazard degree would be.

3.3 Vulnerability of hazard-affected bodies

Ranging from personnel, materials, facilities to environment (Vamanu et al., 2016), hazard-affected bodies are vulnerable in tank accidents. The effectiveness of protective measures is revealed by the rationality of tank layout, the effectiveness of safety valves and control systems, the bearing capacity of cofferdam and fire embankment, and the feasibility of emergency plan and accident treatment. The vulnerability hinges on four factors, namely, exposure, sensitivity, coping capacity and recovery capacity (Zhao et al., 2014). The relationship between each factor and each type of hazard-affected bodies is explained below.

(1) The personnel mainly consist of tank farm patrollers, construction workers, rescuers, central control room (CCR) operators and off-site personnel. Personnel exposure is measured by the frequency and duration of the inspections by onsite personnel, the mobilization of offsite personnel, and the number of personnel. The sensitivity reveals the chance of the personnel being affected by tank accidents. The coping capacity refers to the personnel’s skills, professionalism and mental/physical health facing tank accidents, and the ability to reduce the harms of fire, explosion, poisoning and suffocation. The recovery capacity stands for the time and effect of the recovery of the injured.

(2) The facilities prone to exposure include storage tanks, conveying system as well as supporting devices and structures. The sensitivity and coping capacity of a facility are demonstrated by its material, structure and mechanical features under accidents. The recovery capacity relies on the remedial measures against accidents, such as purchase, maintenance and repair. This capacity is negatively correlated with the period of purchase and maintenance.

(3) Material exposure means that the materials stored in the tanks are affected by the accidents. Material sensitivity describes the likelihood that a material can be substituted by other materials in the process flow under normal production. Material coping capacity measures the effects of tank accidents (e.g. fire, explosion and diffusion) on the materials that can disrupt material supply, impact downstream devices or hinder industrial/social development. Material recovery capacity shows the time consumption and feasibility of timely supply recovery.

(4) The environment refers to both the natural environment and the social environment (i.e. reputation). Environment exposure measures how much tank accidents affect the soil, water, air, plant and microorganism. Environment sensitivity illustrates the proneness of natural/social environment to tank accidents. Concerning social environment, the public reaction varies with the types of facilities. For instance, an accident of paraxylene unit would cause much greater concerns than that of a crude oil unit. Coping capacity weighs the resistance of natural/social environment to tank accidents. Recovery capacity means the ability of natural/social environment to return to the state before the accident.

4. Risk Control Measures

The risk control of tank accidents consists of two steps: controlling the source and blocking the path (Eini et al., 2018). Focusing on inherence safety, the source control can be realized through feasibility study, preliminary design, detailed design and construction. Possible source control techniques include hazard identification study (HAZID), hazard and operability study (HAZOP) and quantitative risk assessment (QRA). The purpose is to identify the process conditions, material properties and device reliability. Since the source control cannot eliminate all the risks, the path blocking should be introduced in the operation phase, such as overall protection and periodical inspection/maintenance (Reniers et al., 2015).

The materials stored in the tanks are inherently dangerous. Because the type of materials is determined by the production requirements and process flow, the inherent hazards could be reduced through the selection of proper process flow, material type and material volume in the design phase. Once the storage facility is completed, the hazard features of the materials are almost fixed. Then, the potential hazards only depend on the effect of protective measures. Here, the risk of tank accidents is controlled based on layer of protection analysis (LOPA) (Lee and Kim, 2015).

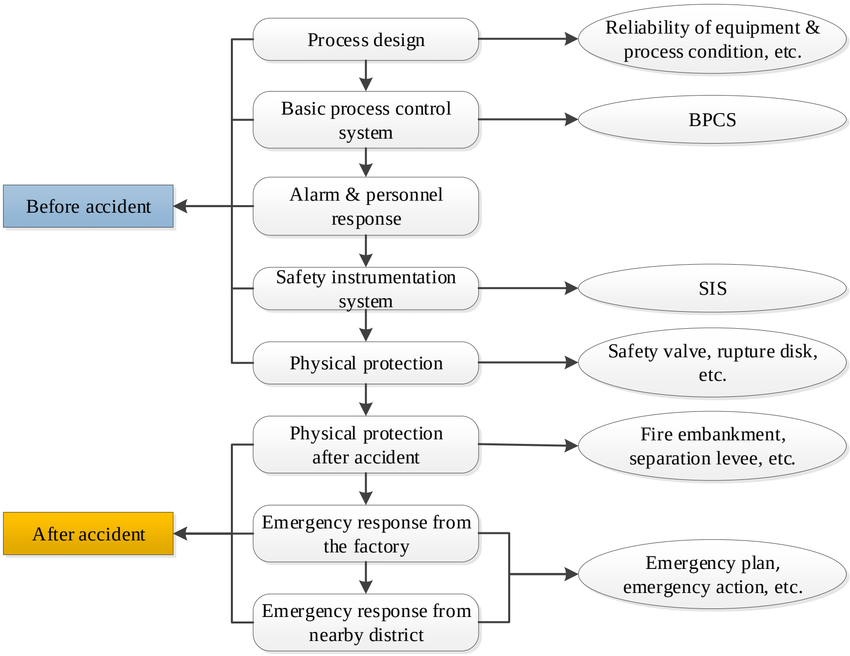

Figure 3: Risk control based on LOPA

The LOPA-based risk control targets the hazards before an accident, the leaked materials during the accident, and the emergency rescue after the accident.

(1) Before the accident, the leakage source, ignition source and leakage concentration must be controlled through inherent safety design. For example, flanges can be replaced by welded joints to reduce the possible leakage points, and carbon steel can be replaced by stainless steel to prevent pipe corrosion. Moreover, lightning rods and antistatic devices should be installed, smoking and open flames should be prohibited, and material feeding should be slowed down, aiming to reduce the chance of electrostatic discharge and electric spark.

(2) During the leakage, the leakage situation should be monitored in real time by multiple sensors (liquid level, temperature, pressure and flow), the distributed control system (DCS), safety instrument system (SIS), combustible gas alarm facilities and closed circuit television (CCTV), such that operators could be notified to adopt countermeasures like suspension of material supply, opening relief valves, etc.

(3) If the protective measures fail, the personnel near the leak points might be poisoned or suffocated and the environment might be polluted if the leaked materials are toxic substances like H_2S. If the leaked materials are combustibles, fire, explosion and similar accidents may occur after the materials reach the explosion limit and encounter ignition source or static electricity. The ensuing shock waves and thermal radiation will cause huge damages to the personnel, equipment and structures nearby. To supress these secondary accidents, the tank farm must be equipped with fire control devices like water sprayers, water cannons and fire extinguishers.

5. Case Study

5.1 Full-surface simulation

The above risk control measures were implemented in an oil tank farm of a coastal refinery in China. To verify the effect of the said measures, a full-surface fire, induced by an external ignition source, was simulated with a turbulent diffusion flame. The flame contains partial circulation reflux. The surrounding air enters the tank through the flame at the centre of combustion. The tank diameter is positively correlated with the depth of air entering the flame (Shebeko et al., 2007; Chang and Lin, 2006).

During the simulation, the wind force was adjusted to explore the effect of wind power on fire propagation and thermal radiation of adjacent tanks. According to the model in Figure 4, the 600m×300m×140m study area contains a total of eight oil tanks. The pipe rank surrounds the tank farm with an interval distance of 2m or plus and the distance between the tanks is 22m. It was assumed that tank 907# caught fire, and the other tanks suffered from thermal radiation. The heat release rate of the crude oil was set to 1.92MW.

5.2 Numerical simulation

The annual mean wind speed is 6m/s at the tank farm. Thus, the wind speed was assumed to be 6m/s when the fire broke out at tank 907#. Besides, it was assumed that initial temperature t_0 = 20℃ was distributed evenly around the tank. Then, the fire development under the wind power was simulated and shown in Figure 5 below.

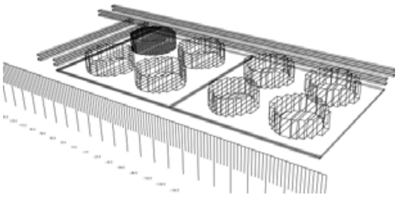

Figure 4: Model of the study area

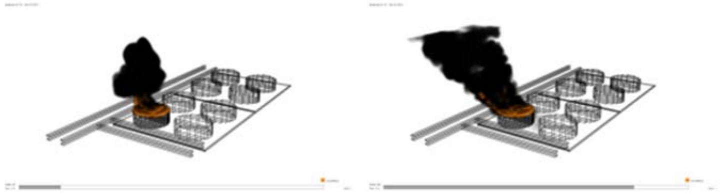

Figure 5: Fire development (12s, 84s)

As shown in Figure 5, the bright yellow colour indicates the burning flame, which releases heat to the surrounding space and the ground; the black colour represents the smoke and combustion products. During the full-surface fire, the oil vapour above the crude oil in the tank was ignited, and the flame propagated through the vapour at the rate of combustion. The fire heated up the surface layer of the crude oil, leading to fast evaporation of the oil. The combustion continued thanks to the interplay between the vapour and the air. The black smoke appeared when the carbon black was not burnt out under insufficient oxygen and moderate temperature.

5.3 Variation in thermal radiation

Then, the thermal radiation to the adjacent tanks and pipe rack was simulated. The time-varying radiation is illustrated in Figure 6. As shown in the figure, the thermal radiation to the adjacent tanks gradually stabilized with the elapse of time. The radiation to the four adjacent tanks surpassed 12.5kW/m^2, which is still below the incident flux (37.5kW/m^2) that can be withstood by the tanks. The radiation to the pipe rack exceeded the incident flux, indicating that the pipe rack might collapse under the fire.

5.4 Variation in temperature

This subsection discusses the tank wall temperature of the surrounding oil tanks and pipe rack. As shown in Figure 7, the temperature impact to the four adjacent tanks reached 70℃ due to the full-surface fire at the wind speed of 6.0m/s, while the temperature impact to the pipe rack reached 120℃. The materials in the pipe might be affected at such a temperature impact. Overall, the ambient temperature increased gradually over time, and the temperature of the adjacent tanks rocketed up with the growth in flame height.

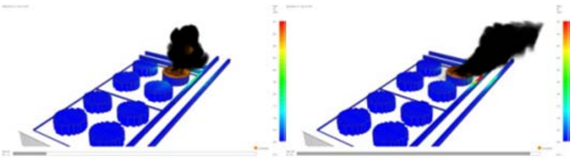

Figure 6: Time-varying thermal radiation (12s, 84s)

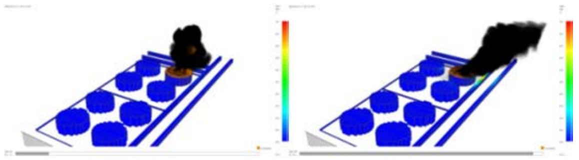

Figure 7: Time-varying temperature (12s, 84s)

5.5 Countermeasures

The above results show that the full-surface fire on tank 907# produced black smoke and thermal radiation, which may result in damages to the surrounding tanks, collapse of the pipe rack, and evaporation of the materials in the pipe. The possible consequences of the fire and explosion include personal casualties, facility damages, material losses, environmental pollution and reputation loss. Through the life cycle of the storage tank, the accidents should be prevented in four phases: the feasibility study and design phase, the operation

phase, the accident phase and the post-accident phase.
(1) In the feasibility study and design phase, the amount of hazardous substances should be minimized, the tanks should be protected by cofferdams, safety valves and relief devices, and the distance and layout of the tank farm should be optimized based on the materials and operation conditions. It is also necessary to adjust the process flow of the materials so as to reduce the hazard degree and vulnerability.
(2) In the operation phase, the staff members should receive trainings on work safety. Moreover, the personnel vulnerability and manual inspection frequency should be minimized by introducing modern methods like robotic inspection so as to reduce the possibility of accidents and the vulnerability of hazard-affected bodies.
(3) In the accident phase, the emergency plan should be implemented in a quick and strict manner, the emergency materials and equipments should be employed and shared fully and quickly, and the emergency rescue teams should be deployed timely, aiming to contain the impacts on hazard-affected bodies.
(4) In the post-accident phase, the reconstruction of the tank farm and recovery of hazard-affected bodies should be enhanced so that the personnel, devices and facilities can be restored to the normal condition as soon as possible so that the vulnerability of recovery capacity can be lowered. An important aspect to the reconstruction and recovery is to enhance the ability to deliver the necessary materials and equipments.

6. Conclusions

After analysing the causes and scope of tank accidents, the risk of storage tank accidents was evaluated from three aspects: accident possibility, hazard degree and vulnerability. Then, several risk control measures were put forward with the aim to control the hazard sources and blocking the propagation path from the perspective of vulnerability, process management and emergency. After that, the proposed measures were validated through a case study on an oil tank farm of a coastal refinery in China. Specifically, a full-surface fire was simulated on one of the oil tanks in the tank farm, the effects of the fire on the adjacent tanks and pipe rack were observed, and several countermeasures were proposed to minimize the hazards. The research findings shed new light on the understanding and prevention of storage tank accidents.

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