Journal of Loss Prevention in the Process Industries 33 (2015) 289–303

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Analysis and assessment of the Qingdao crude oil vapor explosion accident: Lessons learnt

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ARTICLE INFO

Article history:
Received 12 August 2014
Received in revised form
31 October 2014
Accepted 4 January 2015
Available online 5 January 2015

Keywords:
Crude oil vapor
Urban storm drain
Confined vapor cloud explosion
Deflagration
Detonation

ABSTRACT

A devastating crude oil vapor explosion accident, which killed 62 people and injured 136, occurred on November 22, 2013. It was one of the most disastrous vapor cloud explosion accidents that happened in Qingdao's storm drains in China. It was noted that blast overpressure and flying debris were the main causes of human deaths, personal injuries and structure damages. Two months after the accident, it was reported that there were three contentious issues in the investigation report. First issue was the discrepancy between the temperature of the crude oil vapor explosive limits which were measured by the investigation panel and the temperature reported by the local fire department. Second issue was the contradiction between the upper explosive limit and vapor pressure of the crude oil vapor. The last issue was the location of the ignition source which led to the explosion.

In the present study some specific features of this accident and various causes led to the explosion, high casualties and severe damages were analyzed. Three contentious issues in the official investigation report were investigated and tested in detail. The first element tested was the explosive limits and limiting oxygen concentration of the crude oil vapor at different temperatures. Based on theoretical analysis and field investigations, the last two elements in the report were analyzed from multiple perspectives. Based on the TNO Multi-Energy model and PROBIT equations, damage probability of affected people at the leaking site was also estimated. The investigation concluded with a result that precautions need to be taken to prevent flammable gas explosions in the drainage systems. Key steps were explicitly discussed for improving the hazard identification and risk assessment of similar accidents in the future.

1. Introduction

Past accidents have demonstrated that vapor cloud explosions (VCEs) are the predominant cause of the largest losses in the chemical and petrochemical industries where large quantities of flammable materials are stored or processed (Khan and Abbasi, 1999). Approximately 174 VCE accidents have been reported to have occurred from 1940 to 2010 in the world (Lewis, 1980, 1993; Davenport, 1983; Dadashzadeh et al., 2013; Marshall, 1987; Pate-Cornell, 1993; Lenoir and Davenport, 1993; Li and Song, 1991; Michaelis et al., 1995; FDMPS, 1998; Fu and Huang, 1997; Shefner, 1999; Kao and Hu, 2002; Beale, 2006; Mahgerefteh and Atti, 2006; CSB, 2007, 2008a, 2008b; Vautard et al., 2007; Wu et al., 2008; NTSB, 2009; MHIDAS, 2009; Bai et al., 2010; Brambilla and Manca, 2010; Abdolhamidzadeh et al., 2011; Mannan, 2012; Marsh, 2012; Wang et al., 2012; Sharma et al., 2013). From Fig. 1, it can be seen that the number of VCE accidents and death toll have experienced dramatic changes in the past seventy years. The number of VCE accidents started to rise in the 1950s and decreased in the 1980s, while the number of deaths started to rise in the 1960s and decreased in the 1990s. This has four main explanations. Firstly, the chemical industry in developed countries has grown continuously since the early 1950s; more and larger process plants and storage areas have been built, leading to an increase in the transportation and storage of hazardous materials. According, VCE accident losses have increased in both frequency and severity. Secondly, access to information on VCE accidents has improved gradually over time both in developed and developing countries since the 1970s. Thirdly, the high number of deaths in two disastrous VCE accidents, i.e. Mexico City's Liquid Petroleum Gas (LPG) explosion in 1984, Piper Alpha offshore platform explosion in 1988, mainly contributed to the dramatic increase in the number of

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http://dx.doi.org/10.1016/j.jlp.2015.01.004
0950-4230/

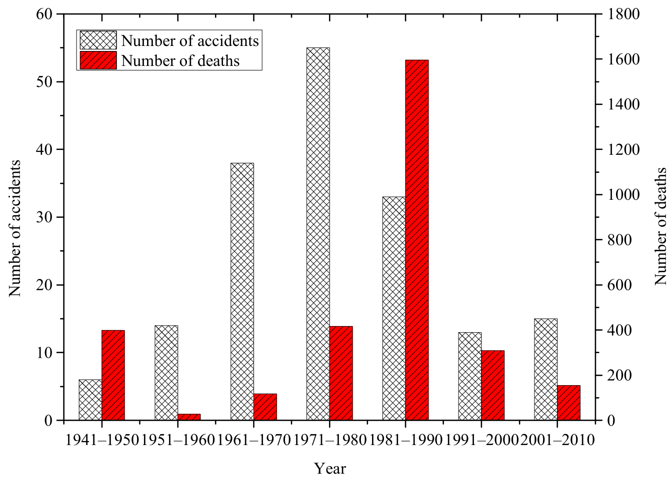

Fig. 1. VCE accident statistics in the world from 1940 to 2010.

deaths from 1981 to 1990. Fourthly, the decreasing incident rate since the 1980s could be explained by general improvements in the safety culture of the chemical and petrochemical industries brought about by strict regulations and more effective operator training. Lessons from the past VCE accidents since the 1980s have also played an important role in reducing similar accidents in subsequent years in developed countries.

Statistics of past VCE accidents show that hydrocarbons with two or four carbon atoms, e.g. acetylene, ethylene, propane, butane, cyclohexane, accounted more than 55% of those incidents. A number of VCE accidents have also been reported involving other reactive chemicals, e.g. methane, hydrogen, liquefied natural gas, gasoline. There are two general classes of spills associated with the reported VCE incidents: the massive single spill produced by the catastrophic or rapid rupture of a storage tank or a process unit, and the continuous leak produced by either a relatively small hole in a tank or a pipeline. In most cases, VCE accidents were associated with the other accidents which have caused further damages, e.g. boiling liquid expanding vapor explosion (BLEVE), flash fire, fireball, domino effects from blast overpressure or missiles.

Nine severe VCE accidents that occurred in China have been documented in the open literature, resulting in 133 fatalities and thousands of injuries. The increase of the VCE incidents in China since the early 1980s is primarily due to rising demand for energy after the initiation of economic reforms in 1978. On the other hand, a series of laws, standards and regulations on plant designs and chemical accidents has not been promulgated and implemented until 2000. Most of the VCE incidents are related to human error during the emergency repair operations, showing that implementation of appropriate measures against the leak of flammable materials was often ineffective and the full lessons were seldom learned. Crude oil, gasoline and diesel were the three main flammable materials involved in those accidents. A further study of the VCE accidents that occurred in China concluded that inadequate process hazard analysis, training and emergency response planning repeatedly contributed to the occurrence of those accidents.

2. Description and analysis of the Qingdao explosion accident

At approximately 10:25 a.m. on November 22, 2013, a series of explosions and fires occurred in the Huangdao district of Qingdao, a coastal city of Shandong province. It was one of the most disastrous industrial explosion accidents that occurred in China due to the crude oil leaking from an underground pipeline into the urban storm drain. The leakage was caused by the accidental rupture of the pipeline which was owned by China Crude oil and Chemical Corporation (Sinopec). Sixty two people were killed and 136 others were injured during this disaster. About 18,000 people were evacuated from the surrounding communities. Nearly 50 buildings with an area of 196,100 m^2, 200 vehicles and 11 main streets were heavily damaged by the blast overpressure and flying debris. More than 3000 m^2 of sea surface was heavily contaminated by the leaking oil. Direct property losses from this accident reached up to 0.1 billion US dollars. Indirect economic losses due to the business interruption and reconstruction of gas, water, heating supply pipelines were hard to estimate. Before the explosion occurred, repair work of the leaking pipeline was conducted for more than 7 h and much of the crude oil was evaporated in the drain. During the initial process of repairing the pipeline, sewage in the drain rose up due to the tide, which resulted in leaking crude oil flowing towards higher elevations. The diffusion range of the crude oil vapors in the drain was expanded enormously. Moreover, the subsequent tide ebbing enhanced the mixing of the crude oil vapors with the air in the drain. The volume of the flammable vapors was further increased. All these factors can greatly increase the intensity of a VCE in such a confined environment.

The exploded storm drain, which was built in 1996, was finally covered with reinforced concrete slabs of pavement two years later in 1998. The storm drain, where the leak occurred, was divided into two sections by Qinhuangdao Road, as shown in Fig. 2(a). The average height of both sections was about 3.08 m. The width of the 25 m long drain in the north section was about 9 m, and the 30 m long drain in the south section was 13 m. The width of the other sections of the drain was smaller than the preceding sections. The leaking pipeline was laid parallel to Qinhuangdao Road. The pipeline (see Fig. 3(a)) was built in 1985 and was operational in 1986. Total annual transfer capacity of the crude oil was 10 million tonnes. The pipeline measured 0.711 m in diameter and it stretched 248.52 km. The leaking pipeline running below the intersection of Qinhuangdao Road and Zhaitangdao Road was actually suspended in the drain. Fig. 2(b) shows the satellite map of the leaking point of the pipeline and Fig. 3(b) describes the layout of the leaking pipeline in the storm drain.

2.1. The leaking point

According to the only repairman who survived the explosion, the leaking point of the pipeline was located in the east wall of the storm drain and had a distance of 15 cm from the wall (shown in Fig. 3(b)). It was estimated that about 2000 tonnes of the crude oil had spilled from a hole with a diameter of 10 cm in the pipeline in about 15 min. Besides, according to several eyewitnesses, there had been a strong smell of the leaking oil in the vicinity of the leaking site during the process of repairing the pipeline. This could further validate that the leaking crude oil had entered the drain, and the oil vapors had fully mixed with the air.

2.2. The sequence of the event

The initiating event of the sequence was caused by the accidental leakage of the crude oil because of the failure of the pipeline. Actually, based on above information, we have known that the leaking pipeline had been in operation since 1986. It had been subjected to deterioration due to aging and improper protection and maintenance. Furthermore, Sinopec's pipe storage & transportation branch, and Shandong local environment protection bureaus had also issued some warnings that the urbanization had threatened the safety of these underground pipelines since 2010. It was sad that these warnings did not arouse the attention of the