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Quantitative risk assessment of fire accidents of large-scale oil tanks triggered by lightning

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ABSTRACT

Severe fire accidents may be triggered by lightning strikes in large-scale oil tank areas. A methodology was proposed to quantitatively assess the fire risk. Based on previous relevant fire cases, three categories of fire accident scenarios are summarized: (A) fire accidents at the rim seal, (B) fire accidents above the floating roof and (C) fire accidents by perforation of the float pan. A generic event tree was built to present the process of fire development of oil tanks with the protection of a fire extinguishing system and a fire brigade. The probability models were proposed to calculate the probabilities of lightning strike, tank wall and floating roof damage/perforation, failure of the fire protection system and timely response of fire brigade. The application of the methodology to a case study provided the probabilities of different forms of accidents for three categories. According to the results of the case study, the probabilities of rim seal fire, local pool fire and full surface fire of large-scale oil tanks are 1.10×10^{-2}, 10^{-8}–10^{-6} and 2.17×10^{-9}, respectively, for Categories A and C, and the probabilities of rim seal fire, local pool fire and full surface fire of large-scale oil tanks are 4.99×10^{-2}, 10^{-8}–10^{-5} and 9.85×10^{-8}, respectively, for Category B. The fire risk by lightning for Category B is relatively higher, which could be reduced by improving the design of the float pan and enhancing the reliability of the components. Compared with the hazard of local pool fire and full surface fire, the risk of rim seal fire is unacceptable; in this case, an inert gas protection system can be introduced to reduce the risk.

1. Introduction

The construction of crude oil reserve facilities has great significance for national economic security and the development of social stability. The use of large-scale steel tanks is one of the important ways of storing crude oil reserves. The most common tanks being used and under construction are floating roof tanks, with a capacity of 1×10^5 m^3 or 1.5×10^5 m^3 [1,2]. Crude oil poses the hazards of fire and explosion and is apt to have accidents in the process of transport and storage, such as leakage and diffusion. Leaking oil or oil vapor could result in an explosion or fire very easily when exposed to an ignition source. If there was not timely and appropriate action to control such accidents effectively, more severe accidents can result. For example, the Domino effect is well-known in major accidents in the chemical process industries [3,4,5].

According to the survey results by Chang [6], approximately 33% of fire and explosion accidents (242 cases) in an area with tanks are triggered by lightning. To reduce the risk of lightning, most countries have established standards of lightning protection for crude oil storage, such as API RP545-2009 in the USA [7] and GB 15599-2009 in China [8]. Overall, these standards have a

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limited effect on reducing the probability of accidents by lightning. Many oil tanks that meet the relevant standards still incur lightning accidents every year, causing serious damage or injuries. Some typical cases are presented in Table 1.

According to the survey results in Reference [6], the risk of fire and explosion of oil tanks triggered by lightning is relatively high. However, it is very difficult to reconstruct the accident scenarios, which leads to scarce research results in this area.

Amos Necci [9,10] studied hazardous material accidents triggered by lightning strike, with a focus on the identification of the event sequences and the accident scenarios following lightning impact on atmospheric tanks. The past accident cases were used to validate the calculation of the expected frequencies of the final scenarios for different types of tanks. However, Amos Necci concentrated primarily on rim seal fire research, without enough consideration of the other forms of accidents. Thus, Amos Necci's analysis of accident scenarios was incomplete. Elisabetta Renni et al. [11] studied the potential forms of accidents based on investigation and statistical analysis of the cases caused by lightning in the chemical process industries. Su Boni et al. [12] proposed a detailed model to provide a quantitative analysis of the risk of lightning strikes and direct damage/perforation. The probabilities for different scales of tanks were determined by the models, but without the analysis of the accident scenarios. Moreover, all of the above studies did not consider the effects of fire brigade on the fire and explosion, which is obviously unreasonable. If the fire brigade arrives in time after the fire and explosion occurred, the accidents could be effectively addressed in most cases, even if the tank fire protection system failed to operate.

From the existing research results, there is still a lack of a comprehensive model, so the quantitative risk assessment of fire triggered by lightning is very difficult to perform. To address this problem, this paper provides a summary of the main accident scenarios via the analysis of accidents based on previous research results in the literature. The proposed method is applied to a case (crude oil reserve in Tianjin City, China) to provide a better assessment and management of the risk of industrial facilities with respect to external hazards due to natural events.

2. Analysis for accident scenarios

Oil tanks struck by lightning can result in a variety of accidents. In accordance with the fire cases listed in Table 1, some common features of these accidents can be summarized as follows:

- Leakage of oil or oil vapor.
- Local fire due to lightning.
- The automatic fire extinguishing system can effectively control and put out the early-rising fire.
- If the fire protection system failed, a full surface pool fire may occur.

To assess the risk of major accidents triggered by lightning, a generic event tree is obtained, as shown in Fig. 1, based on past accident cases involving atmospheric tanks storing hydrocarbons or generic flammable materials.

After a detailed analysis of the cases in Table 1, there are three main accident scenarios for oil tanks, as described below.

Category A: fire accidents at the rim seal

There is a circular space in the range of 200 to 500 mm between the floating roof and the tank wall, which is required for good sealing [13]. If the sealing is too tight, it would be adverse to the movement of the floating roof. If the sealing is too loose, it would

Table 1
Typical fire accidents of floating roof oil tanks trigged by lightning.

Date	Location	Description
03/08/1995	Maoming, China	The effect of the monolayer seal was so poor that oil leakage was severe. The oil vapor was ignited by lightning and resulted in fire. The fire was put out quickly by the automatic fire protection system.
19/07/1996	Ontario, Canada	The mixture inside the tank reached explosion limits. After the floating roof was struck by lightning, the explosion turned over the roof and caused a full surface fire.
13/07/1998	Wuhan, China	The continuous hot weather promoted the volatilization of oil, and excess leakage oil vapor spilled from the failed breathing valve and was collected at the top of the roof. The flammable vapor was ignited by spark due to lightning and spread into the inside of tank via the vent valve, causing a full surface pool fire.
07/06/2001	Louisiana, USA	Heavy rain caused the floating roof to be tripped, and the lightning ignited the exposed oil directly, resulting in a pool fire.
07/08/2006	Yizheng, China	When inductive charge was struck by lightning and produced discharge, the oil vapor between the primary seal and the secondary seal was ignited and caused a rim seal fire. The fire was put out quickly by the automatic fire protection system.
07/07/2007	Baishawan, China	The flammable mixture between floating roof and oil was ignited by lightning, causing a rim seal fire. The fire was put out quickly by the automatic fire protection system.
05/03/2010	Ningbo, China	When inductive charge was struck by lightning and produced discharge, the oil vapor between the primary seal and the secondary seal was ignited and caused a rim seal fire. The fire was put out quickly by the automatic fire protection system.
22/11/2011	Dalian, China	When inductive charge was struck by lightning and produced discharge, the oil vapor between the primary seal and secondary seal was ignited and caused a rim seal fire. Meanwhile, the power supplies of the fire protection system were damaged. After the explosion, a rim seal fire developed into a local pool fire. The fire was put out by the fire brigade in a timely manner.