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Modeling and evaluation of the environmental consequences of fire in atmospheric storage tanks using PHAST software

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ABSTRACT

Fires in atmospheric tanks, which are widely used in chemical process industries, are rare. Still, if they occur, they will have irreparable environmental consequences; thus, this study aimed to model and evaluate the environmental consequences of pool fires and determine the area. The restriction was performed due to the presence of a benzene pyrolysis tank. The consequences of accidents regarding an atmospheric storage tank in a petrochemical complex were investigated with PHAST 8.22 software. After qualitative risk assessment, four scenarios were selected in two weather conditions. Consequence modeling was performed using the relevant data, and after analyzing the results of a pool fire, the resulting restricted area was determined. With increasing leak diameter, the consequences of a fire were wider; the restricted area of about 100 meters in scenario S4 was more than in the other scenarios due to the formation of a pool fire in the hot season. The restricted area resulting from the consequence of the pool fire with a delay in scenario S2 in the cold season was also equivalent to the consequence of both types of pool fires in scenario S3 in the hot season and was 88 meters. Atmospheric conditions also affected the consequences of pool fires. The occurrence of a pool fire also affected some of the side reservoirs. Therefore, designing a comprehensive emergency action plan is suggested in which domino events and the reciprocal consequences of disturbed reservoir accidents are examined through outcome assessment.

1. Introduction

The increasing growth of industries has paved the way for the occurrence of many accidents affecting humans. The oil and gas industry is among the hazardous industries. In these industries, making basic decisions requires identifying and evaluating potential risks or hazards [1-6]. Thus, gaining information and knowledge on the methods of identifying potential risk factors and their correct use in accordance with the activity is an important factor in implementing and maintaining risk management systems, allowing for the correct confrontation with the simplest method and appropriate emergency responses in the shortest possible time

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[7-11]. Storage tanks in process industries contain large volumes of hazardous and flammable chemicals [12,13] and atmospheric tanks are the most widely used tanks in the oil industry. These tanks usually work at an internal pressure of about 2.2 pounds per square inch above atmospheric pressure [14]. Fires and explosions are among the most important and common adverse consequences of chemical emissions in process industries. In this regard, fires occur more than explosions, but explosions are more dangerous and cause more deaths and damages. The damage caused by explosions is much more extensive than fires [15-17]. Fires rarely occur in oil storage tanks, but their occurrence with explosions is followed by catastrophic consequences owing to the storage of significant volumes of fuel or unstable liquids [14]. During a major accident, toxic vapor clouds, overpressure waves, and heat radiation effects instantly claim their toll [18]. Despite efficient risk management, catastrophic events cannot often be avoided over the lifetimes of industries [19]. The Buncefield oil depot accident in the United Kingdom [20], the Jaipur oil depot accident in India [21], and the Glenpool oil depot accident in Oklahoma [22] are examples of accidents that occurred in hydrocarbon storage tanks. Investigation of storage tank accidents from 1960 to 2003 revealed that 85% of these accidents led to both fire and explosions [15,17,23]. Thus, risk identification and qualitative risk analysis, along with risk elimination, correction, control, and monitoring, are essential to the technical needs of consulting, safety, and process engineers in all industries [4-7]. In implementing the risk management process of chemical industries after identifying and evaluating risks, it is necessary to evaluate the severity of the impact and consequences of existing risks in the risk evaluation stage. These impacts are evaluated through the consequence evaluation method. In fact, consequence evaluation is the third and key stage of the four stages of risk evaluation [1,24]. Thus, predicting the behavior of hazardous chemicals emitted from tanks and estimating the consequences and damage caused by fire and explosion are particularly important [15,25]. Consequence modeling is used for this purpose. Consequence modeling is one of the safety engineering analyses that can predict the majority of accidents and reduce the resulting damage [26]. A lot of software is used to model explosions and fires and evaluate their consequences. Most of them do not have high flexibility due to the large volume of calculations, time consuming execution, and inability to perform multi-purpose tasks [26, 15, 27,28]. Today, multiple software models such as Hazard Prediction and Assessment Capability (HPAC), Dense Gas Dispersion Model (DEGADIS), Process Hazard Analysis Software Tool (PHAST), and Areal Location of Hazardous Atmosphere (ALOHA) [29,30], Response Surface Analysis (RSM), and MPACT model have been developed to predict the spread of toxic and dangerous materials, each having characteristics consistent with its application [31]. Investigation of various consequence modeling models, such as DEGADIS, SLAB, HGSYSTEM, Response Surface Analysis (RSM), MPACT model, ALOHA, and PHAST, suggests that each has its own positive characteristics and criteria. In this regard, PHAST has capabilities that others do not have [32,33]. This software includes a wide range of pure materials lighter and heavier than air and can model a mixture of materials [24]. Given what was stated, and considering what has occurred in storage tanks in recent years, as well as reviewing past studies and considering that atmospheric storage tanks have been investigated less than under pressure tanks, the present study was conducted to model and evaluate the consequences of pool fires following leak and outflow of material and to determine the zone restricted due to the presence of benzene pyrolysis tank in a process industry.

2.Materials and methods

This study is based on a hypothetical scenario in a petrochemical complex located in Bandar Mahshahr in Khuzestan province, Iran, in 2021(Figure 1). Its longitude is 49 degrees and 13 minutes with a latitude of 30 degrees. The present study analyzed the modeling of the consequence of a pool fire in the atmospheric storage tank of benzene pyrolysis.

Fig. 1. Petrochemical complex located in Bandar Mahshahr, Khuzestan, Iran.

Identifying vulnerable zones and specific risks is crucial in analyzing the results, and not identifying a series of risks leads to not evaluating their consequences [35]. In the present study, the Hazid evaluation method was used to identify risks qualitatively and prioritize risks to select possible scenarios. A scenario is an event or set of events that cause rupture or leaks in process equipment (tank, reservoir, pipe, etc.) containing toxic and flammable hazardous materials [27]. The following can be used to select the appropriate scenarios for modeling: records of possible accidents in the chemical process industry, studies conducted in the past, and the scenarios mentioned by the DNV reference (a reputable company that determines the diameter of the leak from tanks and presents different tables based on leaks occurred in important process industry events) [9,18]. In the present study, the guidelines provided by DNV were used to select the leak diameter and four material leaks scenarios were selected from gaps 10, 50, 150, and full tank rupture (Table 1). The following information is needed to model the consequence using PHAST software: type, amount, temperature, and pressure of the material; diameter and height of the leak; height of the retaining wall; environmental parameters (temperature, humidity, wind speed, atmospheric stability, and instability); and some other information. Hence, the information needed to execute the software, including the parameters related to the tank (Table 2) and information about the environment (Table 3), was collected.

Table 1. Selected scenarios in the study.

Scenario name	Leak diameter (mm)	Time (min)	Emission method
S1	10	10	Horizontal
S2	50	10	Horizontal
S3	150	10	Horizontal
S4	full rupture	-	-

Then, the atmospheric stability state in the study zone was considered in two time intervals according to the Pasquill model. In the first six months (warm season), the stability class was considered on day E, and in the second six months (cold season), it was considered at night F (Table 3).

Table 2. Studied process information.

Material	Tank type	Volume (m^3)	Height (m)	Diameter (m)	Temperature (°C)	Pressure
Benzene pyrolysis	Floating roof	3032	11.725	19.5	40	Atmospheric

Table 3. Studied weather conditions.

Season	Warm season (first six months)	Cold season (second six months)
Daytime and night	daytime	night
Average air temperature (°C)	46	12
Average humidity (%)	51	81
Degree of stability	E	F
Wind speed (M/ S)	9.5	7.5

It should be noted that the impacts of leaks can be modeled for all the days of the year, but as it is bulky and impractical, only the worst weather conditions were studied. The mean wind speed and the mean day and night temperatures were extracted from the meteorological data of the study zone, including weather condition reports of recent years and a review of other studies conducted in this zone [36,37]. It should be noted that to determine the worst state, due to the independent impact of temperature, wind speed, humidity, etc., on the absolute dispersion of materials in space, particular weather conditions cannot be considered as the worst state beforehand [38]. The ups and downs of the land around the emission site were also considered 1 meter according to the surrounding environment. Then, the desired data were entered into the PHAST 8.22 software; the possible consequences were identified, and the results were extracted in the form of various graphs. In the present study, to evaluate the fire consequence, three levels of radiation were considered in accordance with the Total gs253 reference: 37.5(Causing damage to units, equipment, and processes and the immediate death of people at risk), 12.5 (The minimum energy required to create sparks in wooden pallets and melt plastic materials), and 4.7(Causing pain in people who are exposed to it for at least 20 seconds, first degree burns, kW/m^2). According to this reference, the zone restricted by a scenario is a zone that includes equipment installation boundaries in the process units and should be controlled by the setting up and operation group. In the case of a pool fire in process units, the criterion of fire radiation was 4.7 kW/m^2 (this number also includes thermal radiation caused by sunlight) [39]. Relevant conditions were considered in this study; after entering the required information and modeling the consequence, the probable results for each scenario were examined, and its output results were extracted in the form of graphs. In the present study, after reviewing the results of consequence modeling, the graphs obtained from the 10 mm leak scenario were ignored due to less severe consequences; the results of the graphs obtained from the 50 and 150 mm leak, total tank rupture, and instant emission of all materials, which had higher consequences and covered other possible scenarios, were further analyzed to compare the final results.

3. Results and discussion

In general, the consequences of the emission of a material can be divided into three categories: fire, explosion, and toxicity impact of the emitted materials in the environment [39]. There are different types of fire, including jet fire, which is caused by the ignition of a jet caused by the outflow of pressurized gas from a hole [40], and flash fire, consisting of short-term combustion of flammable gases that are in the flammability range [41]. When a flammable liquid forms a pool around a tank, the possible accident event is a pool fire since a pool fire is created when vapors reach a source of ignition [42,43]. The second possible consequence is an explosion, which causes a shock wave and suddenly spreads to the surrounding environment, increasing pressure at each point. The consequences of the explosion are investigated based on the generated shock wave [40-42]. There are two factors influencing the consequences of inhaling toxic materials. The first is the concentration of the material being inhaled, and the second is the duration of its inhalation [41]. In general, in examining the consequences of a pool fire, the amount of radiation generated is evaluated. In this study, three levels of radiation were evaluated. The consequence of a radiation level of 4.7 kW/m^2 causes grade 1 burns and pain in people who are exposed to it for at least 20 seconds. A radiation level of 12.5 kW/m^2 generates the minimum energy required to create sparks in wooden pilots and melt plastic materials. The radiation level of 37.5 kW/m^2 will cause damage to the units, equipment, and process and the immediate death of people, making it the most dangerous level of radiation. According to the risk evaluation in this study, the most probable scenarios in the benzene pyrolysis tank will include the leak and the outflow of material, followed by the possibility of fire or explosion. Thus, four scenarios were studied in two weather conditions, and since the probability of a pool fire in the atmospheric storage tanks was more likely, the consequence of this fire was investigated. In scenario S2, if a leaked material on the ground immediately hits the source of a spark, it will cause an early pool fire. If it is formed in the first six months of the year, a fire with a radiation intensity of 115 kW/m^2 will be formed, receiving the maximum amount of radiation up to a distance of 12.5 m. At this distance, it will have the highest rate of damage and death. In general, the consequences of this fire will be observed up to a distance of 59 m. Also, if an early pool fire is formed in the second six months of the year, a fire with a radiation intensity of 118 kW/m^2 will form, which receives a maximum amount of radiation up to a distance of 13 m, and the consequences can be observed up to a distance of 52 m (Figure 2).

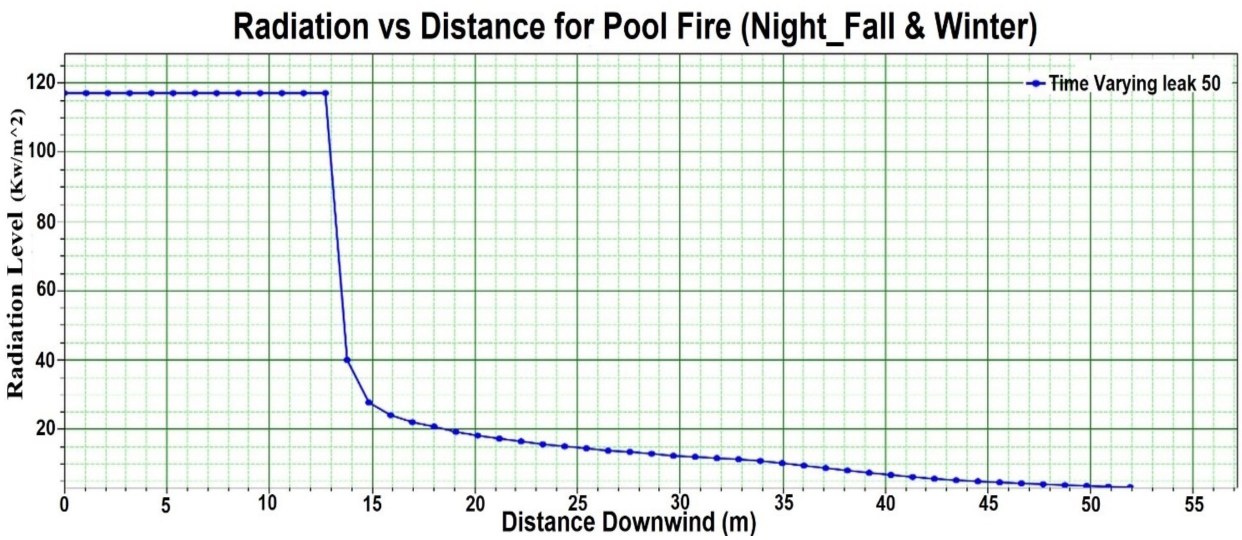

Fig. 2. Early pool fire intensity in the second six months of the year in Scenario S2.

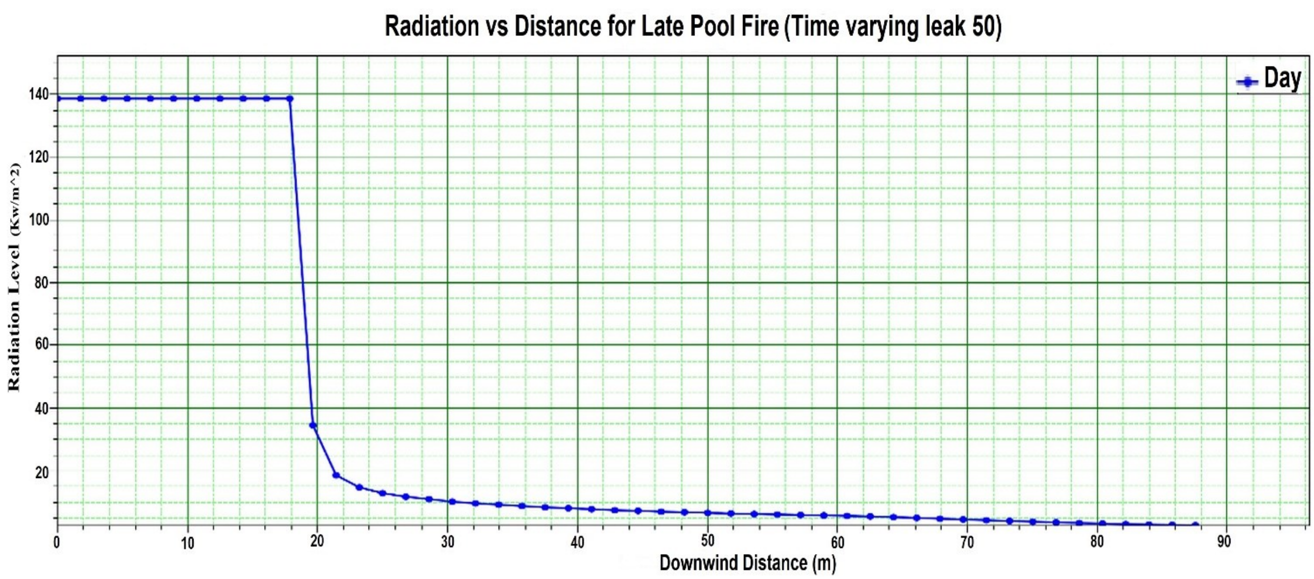

Fig. 3. Late pool fire intensity in the first six months of the year in Scenario S2.

Examining the modeling results of the benzene pyrolysis tank showed that in case of occurrence of an early pool fire as a result of Scenario S3 with variable emission rate, a fire with a flame diameter of 35.328 m and a flame length of 53.633 m was formed; in the weather conditions of the first six months of the year, the intensity of fire radiation will be 138 kW/m^2 and will continue up to a maximum distance of 87.525 (Figure 4).

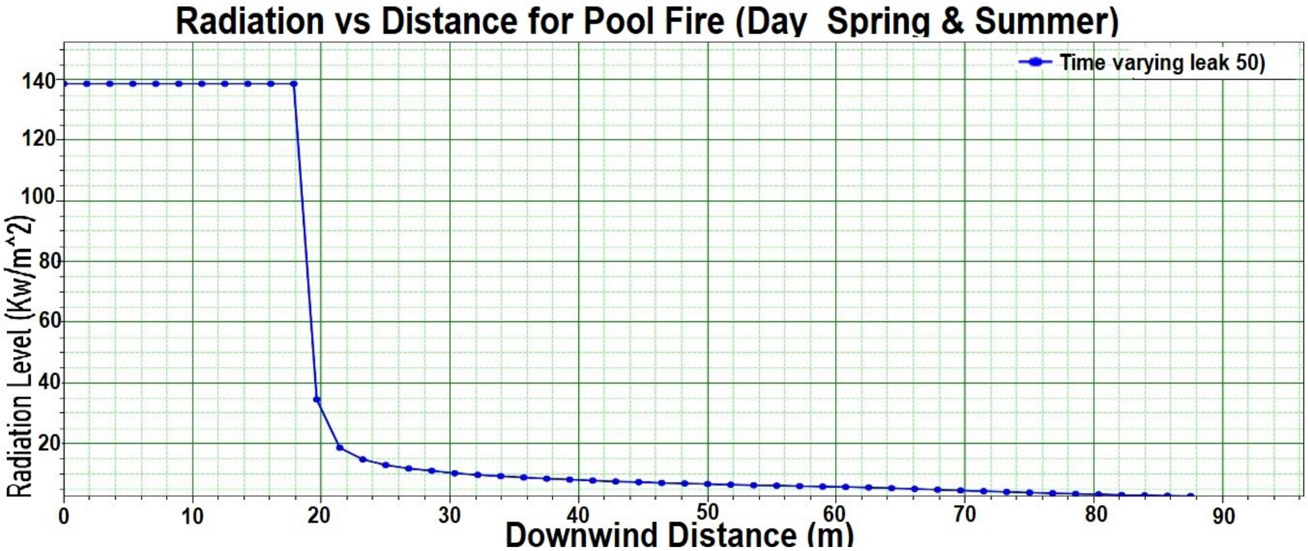

Fig. 4. Early pool fire radiation intensity in Scenario S3 in the first six months of the year.

A fire with a flame diameter of 35.326 m and a flame length of 453.523 m with a radiation intensity of 138 kW/m^2 will be formed in the weather conditions of the second six months of the year; its impact will be observed up to a distance of 71 m (Figure 5).

In the case of the occurrence of an early pool fire in Scenario S3, a fire with a flame diameter of 35.33 meters and a flame length of 63.33 m will be formed; in the first six months of the year, the maximum radiation intensity of this fire will be 138 kW/m^2 and can be observed with this intensity, and the radiation and the consequences of this type of fire will be observed at a distance of 88 m. In the second six months of the year, a fire with a flame diameter of 53.33 m and a flame length of 45.52 m will be formed with a maximum radiation intensity of 138 kW/m^2, which this intensity will be observed up to a distance of 16 m; the radiation of this fire will be observed up to a distance of 71 m in the second half of the year. Compared to an early pool fire, in the first six months, the length of the flame formed in a late pool fire will be longer. In the full rupture scenario (S4), if a late pool fire is formed, a fire with a flame diameter of 43.29 m and a flame length of 61.76 m will be formed. In the weather conditions of the first six months, the intensity of fire radiation will be 139.92 kW/m^2, and its impacts can be observed up to a distance of 99.45 m. The zone affected by this fire is shown in Figure 6

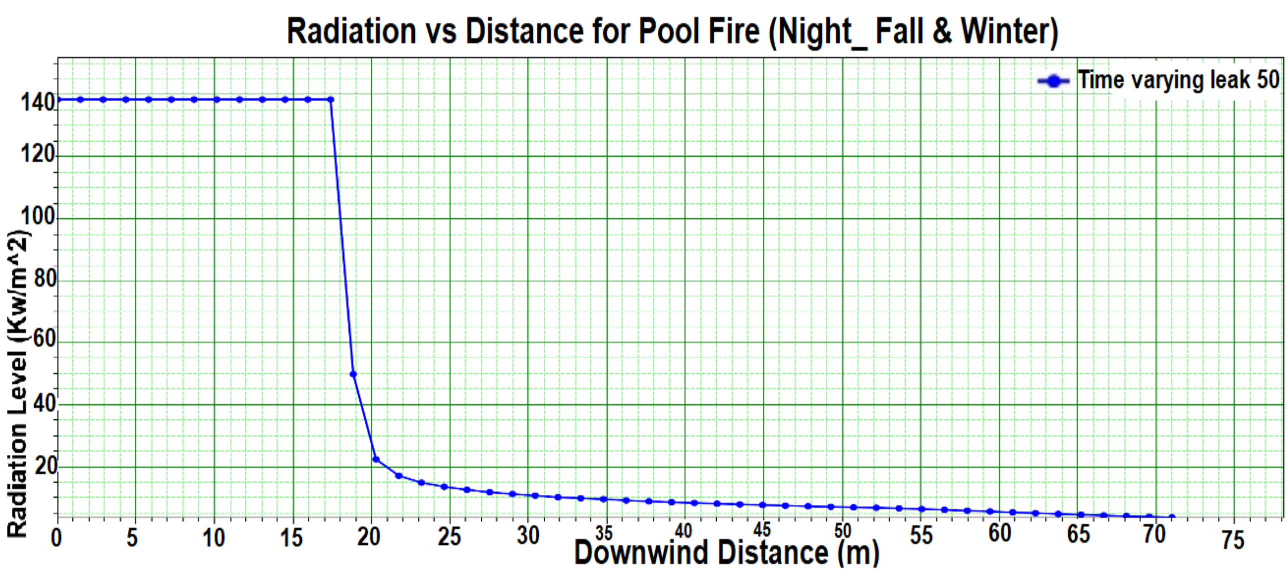

Fig. 5. Early pool fire radiation intensity in Scenario S3 in the second six months of the year.

Fig. 6. Late pool fire affected zone in scenario S4 in the first six months of the year.

In the weather conditions of the second six months, a fire with a flame length of 52.42 m, with a radiation intensity of 139.72 kW/m^2 will be formed, and its radiation will be observed up to a distance of 88.45 m. The contours caused by the pool fire (m^2) can be seen in Figure 7. The figure shows that in the zone of about 23 m, the highest probability of death and damage can be predicted.

The results of investigating the zone affected by the radiation intensity of 37.5 kW/m^2 are shown in Table 3. It has the highest probability of death for at-risk people (98%) and damage to units and process equipment in the studied scenarios.

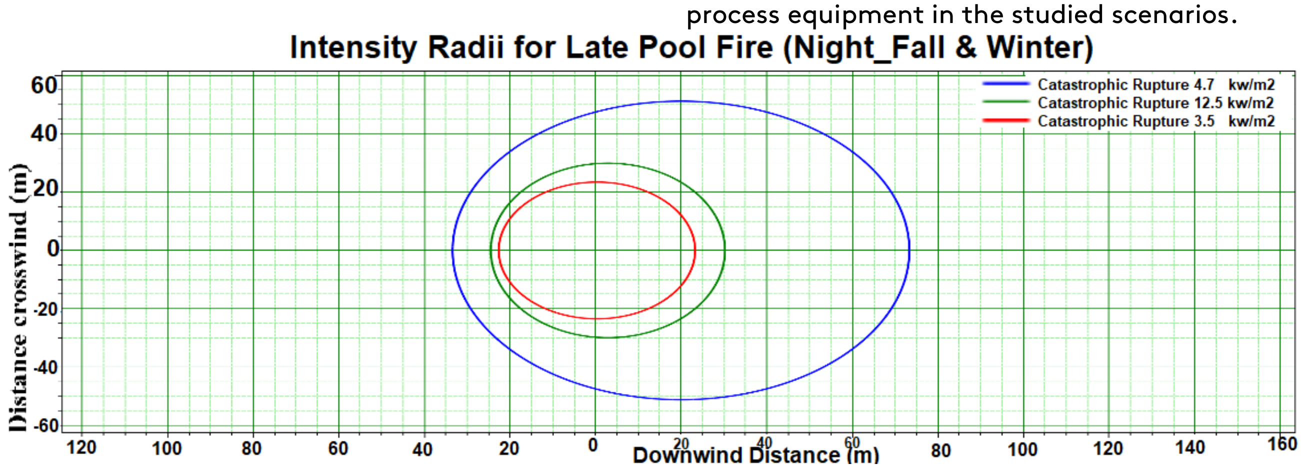

Fig. 7. Pool fire intensity contours in scenario S4 in the second six months of the year.

Table 4. The zone affected by pool fire (radiation intensity of 37.5 kW/ m^2).

Weather conditions and scenario	Scenario S2 in the first six months	Scenario S2 in the second six months	Scenario S3 in the first six months	Scenario S3 in the second six months	Scenario S4 in the first six months	Scenario S4 in the second six months
Zone affected by early pool fire (m^2)	19.5	14	20	19	24	23
Zone affected by late pool fire (m^2)	20	14	20	19	24	23

Table 5. The zone restricted due to pool fire in the studied scenarios.

Weather conditions & scenario	Scenario S2 in the first six months	Scenario S2 in the second six months	Scenario S3 in the first six months	Scenario S3 in the second six months	Scenario S4 in the first six months	Scenario S4 in the second six months
the zone restricted by early pool fire (m^2)	59	52	88	71	100	80
The zone restricted by late pool fire (m^2)	88	71	88	71	100	80

Based on the results of Table 4, the zone affected by the pool fire in the full rupture scenario can have the highest death probability. This study investigated the zone restricted by a pool fire in the benzene pyrolysis tank (Table 5). The results showed that the restricted zone would be a maximum of about 100 m in the first six months of the year in scenario S4 due to the formation of both types of pool fire.

Almost 15 to 30% of the oil and gas industry costs are related to safety and prevention of air pollution [38,44]. Modeling using software helps diagnose possible consequences and damages caused by it. In the present study, PHAST software was used for consequence modeling, which is one of the most widely used and reliable software for modeling a material leak [45,46]. The modeling results showed that full rupture scenarios and scenarios that are related to leak from the 150 mm gap are the most hazardous scenarios of the benzene pyrolysis storage tank; this result is consistent with the study conducted by Bahmani et al. [15]. In atmospheric tanks, one of the most common consequences is a pool fire. In the present study, it was observed that by increasing the leak diameter from 10 mm to complete rupture, the radius of thermal radiation caused by fire increases significantly, which is consistent with the study conducted by Kamil et al. [47]. Examining the consequences of the benzene pyrolysis tank showed that most were related to a pool fire. Examining the consequences of a pool fire in the studied scenarios showed that in Scenario S2, the intensity and consequence of a late pool fire were more than those of the zone affected by an early pool fire. In Scenario S3, although both types of pool fires were formed in the warm and cold seasons with the same intensity of radiation, the maximum distance affected or the restricted zone restricted due to the formation of pool fires in the first six months of the year (warm season) was more; in the scenario related to the full rupture of the atmospheric storage tank, most hazards and casualties were observed since the volume of outflow material was higher than the other scenarios. This result was consistent with that of the study conducted by Filippini et al. [37]. Also, the highest intensity of pool fire radiation in this study was observed in Scenario S4, which was equivalent to 139 kW/m2 and was much higher than the intensity of radiation caused by a pool fire in a study conducted by Wang et al. [41]. The results of Scenario S4 also show that if both types of pool fires occurred, they would have an almost equal restricted zone and affected zone, which is more than the other studied scenarios. However, in this scenario, its restricted zone in the second six months will be greater. Also, the results of this study revealed that the impact of atmospheric stability on fire consequence decreased with increasing leak diameter, and increasing air temperature and wind speed increased it so that the consequence of a pool fire in the warm season in Scenario S4 had the greatest consequence. Also, any gap in the atmospheric storage tank could lead to a pool fire with high consequences, so that the consequence of a late pool fire in Scenario S2, the affected zone and distance would be equivalent to the consequence of a pool fire in Scenario S3; the consequences of the pool fire would be higher in the warm season than in the cold season. Studies suggest that weather conditions impact the consequences of pool fires, so the consequences of such fires were more in the summer. Thus, the need for tank-cooling systems and cooling of side tanks to prevent fires would increase. In the case of the occurrence of a pool fire, some of the side tanks would also be affected by this fire.

4. Conclusions

In general, the results of this study showed that with increasing leak diameter, the consequences of a fire would be more extensive. The probability of death and damage increased since the volume of materials emitted suddenly increased so that the affected zone with a high death probability was observed in the full rupture scenario; the zone restricted due to the presence of this fire in the studied tank was also higher in this scenario than in other scenarios. The consequences of a pool fire will be greater in the hot season than in the cold season. Also, surveys showed that atmospheric conditions affect the outcome of a pool fire, so the consequences of such a fire were greater in the summer; thus, there is a need for tank cooling systems and cooling of the side tanks to prevent the occurrence of a fire. Hence, designing a comprehensive emergency response plan using consequence evaluation that examines domino events, impacts, and mutual consequences resulting from the accident in the tanks is recommended.

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