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Biannual Peer Reviewed Journal Issued by Research and Consultation Center , Sabratha University

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Editorial

We start this pioneering work, which do not seek perfection as much as aiming to provide a scientific window that opens a wide area for all the distinctive pens, both in the University of Sabratha or in other universities and research centers. This emerging scientific journal seeks to be a strong link to publish and disseminate the contributions of researchers and specialists in the fields of applied science from the results of their scientific research, to find their way to every interested reader, to share ideas, and to refine the hidden scientific talent, which is rich in educational institutions. No wonder that science is found only to be disseminated, to be heard, to be understood clearly in every time and place, and to extend the benefits of its applications to all, which is the main role of the University and its scholars and specialists. In this regard, the idea of issuing this scientific journal was the publication of the results of scientific research in the fields of applied science from medicine, engineering and basic sciences, and to be another building block of Sabratha University, which is distinguished among its peers from the old universities.

As the first issue of this journal, which is marked by the Journal of Applied Science, the editorial board considered it to be distinguished in content, format, text and appearance, in a manner worthy of all the level of its distinguished authors and readers.

In conclusion, we would like to thank all those who contributed to bring out this effort to the public. Those who lit a candle in the way of science which is paved by humans since the dawn of creation with their ambitions, sacrifices and struggle in order to reach the truth transmitted by God in the universe. Hence, no other means for the humankind to reach any goals except through research, inquiry, reasoning and comparison.

Editorial Committee

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- Keywords, max. 5 words.
- Introduction.
- Methodology.
- Results and Discussion.
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Invitation

The Editorial Committee invites all researchers "Lectures, Students, Engineers at Industrial Fields" to submit their research work to be published in the Journal. The main fields targeted by the Journal are:

- Basic Science.
- Medical Science & Technology.
- Engineering.

Refereeing

The Editorial Committee delivers researches to two specialized referees, in case of different opinions of arbitrators the research will be delivered to a third referee.

Editorial Committee

CONTENTS

EVALUATION OF DOMINO EFFECT CAUSED BY POOL FIRE IN A TANK FARM

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Abstract

Major hazard installations (MHIs) such as oil refineries, petrochemical plants and terminals use large capacity storage tanks for storing crude oil and by-products. Pool fire is one of the most common types of storage tank fire incidents. This technical article aims to investigate the domino effect from a pool fire in a tank farm consist of eight large floating roof storage tanks. Four storage tanks have been studied. A crude oil storage tank was selected as the primary tank (source tank). Point source and plume solid models were used for the estimation of the thermal radiation. It has been noted that the thermal radiation from the source tank to the adjacent tank in the same dike exceeds the threshold heat radiation level and might resulted in domino effect however the thermal radiation from the source tank alone does not reach the threshold level for the tanks in the other dike. Also, it has been found that the thermal radiation from both the primary and secondary tanks just reach the threshold level for the farther away tank in the other dick. The domino effect occurs provided that the firefighting system is not activated and the emergency response team does not intervene within ten minutes.

Keywords: Major Hazard Installation; Storage Tank; Pool Fire; Thermal Radiation; Dominio Effect.

Introduction

Major hazard Installation (MHIs) such as refineries, petrochemical plants and terminals are usually use large capacity storage tanks for storing of crude oil and by products. The major hazards which are resulted in from the operation of MHIs are fire, explosion and toxic release (Crowl et al., 2000). The world has witnessed many tank fire incidents (Persson, 2004). Pool fire is one of the most common types of fire accidents in chemical process industry (CPI). Buncefield, UK (2005), Sitapura, India (2009), and Puerto Rico, USA (2009) are the examples of very large and persistent pool fires which occurred in tank farm (Ahmadi et al, 2019). The pool fire thermal radiation might affect the adjacent storage tanks resulted in domino effect. Domino effect is used to describe a chain of accidents in which a primary accident escalates into higher-order accidents. Such accident scenarios are more likely to cause massive damage to people, assets, and the environment than stand-alone accidents. Domino effect is any incident that began with a minor accident that can trigger a sequence of events that cause damage over a bigger area and lead to severe consequences. An accident can be categorized as domino effect if there are these three concepts involved: (1) a “primary” event that occurs in a certain unit, (2) the propagation of the accident to one or more units, in which “secondary” accidents are triggered as a result of the primary event, (3) an “escalation” effect that results in overall increase in effects, with secondary accidents being more severe than the primary one (Darbra et al., 2010). There are two main patterns identified for propagation and escalation: (1) direct escalation and (2) indirect escalation.

Previous studies indicate that the frequency of the domino effect has increased in the chemical and process industries in recent decades (Jun WU et al., 2015). Disasters caused by domino effects, such as the BP Deepwater Horizon explosion, Buncefield oil depot fire, Puerto Rico's CAPECO explosion and fire accident, and the Jaipur fire accident have demonstrated the vast damage caused to society. The pool fire accounts for 44 percent of all accident scenarios that escalate to a domino effect (Ruochen Yang, et al., 2020). The possibility of a domino event caused by a pool fire may vary under different conditions. The impact of a pool fire on adjacent equipment and personnel depends on several factors, including fuel properties, pool size, the distance between the fire and target equipment, and meteorological conditions. (Ruochen et al., 2020). As these frequent and dangerous accidents occur in the chemical industry, the pool fire is often blamed as one of the primary accidents triggering a domino event (Zhuang Wu et al., 2020). A historical analysis of 261 accidents involving domino effects showed that storage areas are the most probable starters of a domino effect (Farid, 2011). Kadri (2011) also highlighted that the past domino accidents reveals that the most typical primary incidents for a domino effect sequence are explosions (57%), followed by fire (43%). It was highlighted that in Taiwan some storage tanks fire or explosion makes more disasters, that because there was not enough safety distance between storage site and the other adjacent areas (Cheng et al., 2011). The storage tanks 2 and 12 at Libyan Ras Lanuf terminal were exposed to catastrophic damage due to the armed assault. This has resulted in 400,000barrel reduction of crude oil storage capacity (Gary Dixion, 2018). This technical article aims to present an overview on the evaluation of domino effects which results in from storage tank pool fire in a large-capacity crude oil storage tank through a case study.

Thermal Radiation Estimation

There are several models proposed in literature to estimate the thermal radiation and its effects (Zuzana et al., 2016 and Roberto et al., 2016). It was highlighted that semi-empirical models are the most widely used for routine hazard estimation because they are easily understood and mathematically uncomplicated. There are two types of semi-empirical models: point source models and solid plume radiation models. Pool fire semi-empirical models are composed of several submodels schematically shown in Figure (1).

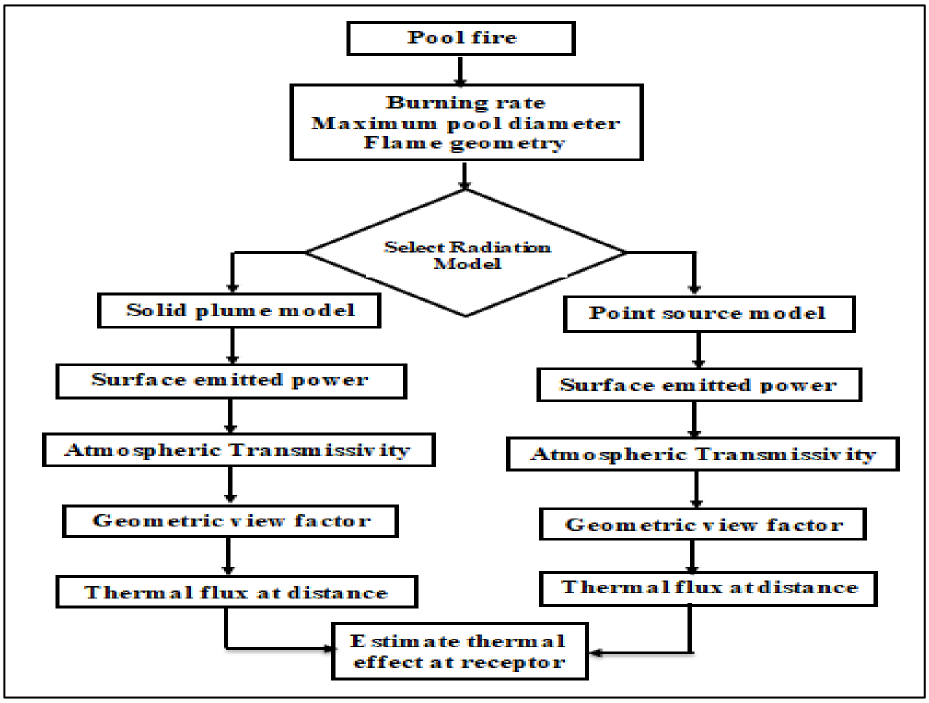

Figure (1): Pool Fire Models Schematic Diagram (Zuzana et al., 2016).

The first step in calculating the consequences of a pool fire starts with the calculation of the burning rate. When a spilled liquid is ignited, a pool fire develops. The most important parameters of a burning pool which determine the flame shape are the flame length. The most widely used flame height correlations are those of Heskestad (Heskestad, 2002), and Thomas (Ufuah et al., 2011). The flame height can be calculated for still air and under wind conditions as shown in Table (1).

Table (1): Pool Flame Length Correlations.

Correlation Author	Equation		Wind
Thomas (1963)	$L/D = 42\left[m_B/\rho_a\sqrt{gD}\right]^{0.61}$	Eq. (1)	No
Heskestad (2002)	L= 0.23$Q^{2/5}$ - 1.02D	Eq. (2)	No
Thomas (1963)	$L/D = 55\left[m_B/\rho\sqrt{gD}\right]^{0.67} u^{*0.21}$ $cos\theta = 0.7[u_W/(gm_BD/\rho_a)]$ $u^* = u_W/(gm_BD/\rho_V)^{1/3}$	Eq. (3) Eq. (4) Eq. (5)	Yes
Moorhouse (1982)	$L/D = 6.2\left[m_B/\rho\sqrt{gD}\right]^{0.254} u^{*-0.044}$	Eq. (6)	Yes

The steps and equations to estimate the heat flux by using the point source and solid plume models are summarized in Figure (2).

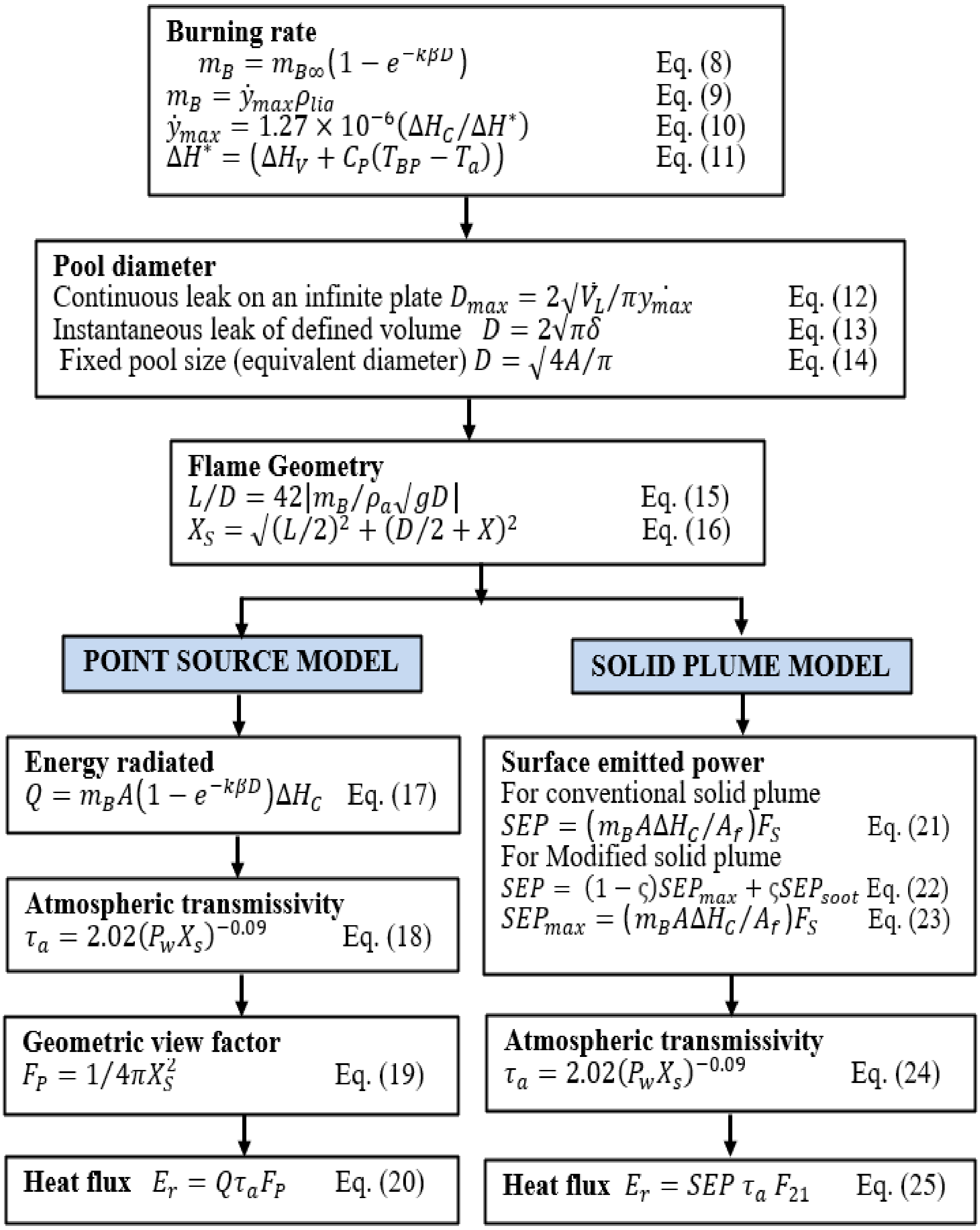

Figure (2): Point Source Models Steps and Equations.

Tank Layout and Spacing

In order to avoid tank fire or explosion incidents spreading to neighboring areas and evacuate people, it is essential to keep a safe distance between storage tank and other nearby areas. Ideally, tank layout should be optimized to ensure that there is sufficient access to tanks for firefighting and to minimize the risk of escalation in the event of a tank fire. Setting reasonable safety distance (shell-to-shell) between tanks can effectively prevent the occurrence of domino accident. Table (2) summarizes the codes recommended safe separation distance between tanks.

Table (2): Safe Separation Distance between Tanks.

Codes	Tank Spacing (Shell-to-Shell) m
Marsh Companies Marsh (2015)	1 x the diameter of the largest tank with an absolute minimum of 15 meters.
HSE – 176 Marsh (2015)	15 m for tanks diameter above 45 m diameter.
The NFPA-30 code Marsh (2015)	1/6 sum of adjacent tank diameters
KLM Technology Group Marsh (2015)	Half the diameter of the larger tank, but not less than 10 m and need not be more than15m.
OISD Marsh (2015)	Tanks with diameter exceeding 50 m, (D + d)/4
China code GB 50,074-2014 (Fu-zhen, 2018)	0.4 diameter
Taiwan's regulations (Cheng et al, 2011)	The spacing shall be one-sixth (1/6) of the sum of the diameter of two abutted tanks

Thermal Radiation Consequences

It was highlighted that thermal fluxes and radiation associated with storage tank fires pose significant hazards to people and facilities. Thermal radiation consequence on people could range from first degree burn injury to fatality, while consequences on facilities could involve the weakening of materials stress bearing capacity leading to structural failure and possible loss of containment of hazardous materials (Dili, 2016). It was highlighted that a heat flux of $5kW/m^2$ is commonly used as a criterion to specify exclusion zones for emergency personnel (Luketa, 2022). The Department of Housing and Urban (HUD) has established radiation flux levels of $31.5kW/m^2$ for buildings and $1.4kW/m^2$ for people as guidelines in determining an Acceptable Separation Distance (ASD) between a fire consuming combustible liquids or gases and nearby structures and people (McGrattan, 2000). Table (3) summarizes the Level of heat flux effect on people and damage to steel structure. It was also proposed that the threshold value is $15\,KW/m^2$ for over 10 minutes when the atmospheric tanks are affected by heat radiation (Fu-zhen, 2018).

Table (3): Level of Heat Flux Effect on Workers and Steel Structure.

Radiant flux (kW/m^2) level	Pain and injury to human / process equipment and structure damage (after 30 minutes)
1.0	No harm – solar constant on a summer day.
2.1	Pain after 1 minute
5	Pain after 10s. 1st degree burn after 20s. 2nd degree burn after 30s exposure to bar skin.
15	The threshold of heat radiation flux that will cause accidents in adjacent tanks
31	Steel deformation
37	Process equipment and structure damage

Mechanism of Domino Effect in Pool Fire

1 - Characteristics

It was found that the domino effect has at least the following three characteristics (Fu-zhen, 2018).

1. A primary accidental scenario (usually as fire, explosion) occurred;
2. The propagation of the primary accident to one or more adjacent units, due to an "escalation vector" (thermal radiation, overpressure and fragment) generated by the primary scenario;
3. An "escalation" effect that leads to a general increase in consequences than overall consequences more severe than those of the primary event.

2 - Escalation vectors and thresholds

It is believed that the thermal radiation produced by fire (e.g. pool fire, jet fire, flash fire, fireball), overpressure and fragment produced by explosion, are the escalation vectors leading to the occurrence of the second or third accidents. The escalation threshold is an important criterion for the identification of domino accident.

3 - Theoretical models of thermal radiation

The theoretical models of flame height and thermal radiation flux have been summarized in Table (2).

4 - Probability analysis

The escalation probability can be calculated from the cumulative expression for a normal Gaussian probability distribution function, i.e. Equation

$$\boldsymbol{P_d = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-x^2/2} dx} \qquad \textbf{Eq. (26)}$$

The "Probit model" can be effectively used to evaluate the Probit value for escalation by analysing the relationships between the time to failure (ttf), threshold values (I) and volume (V). Table 4 summarizes the Probit models used in the present study to evaluate the escalation probability for atmospheric and pressure vessels affected by thermal radiation.

Table 4: Models for Escalation Probability Due to Thermal Radiation.

Escalation Vector	Target Equipment	Probit Models	
Radiation	Atmospheric	$Y = 12.54 - 1.847ln(ttf)$	Eq. (27)
		$ln(ttf) = -1.128ln(I) - 2.667 \times 10^{-5}V + 9.887$	Eq. (28)
	Pressurized	$Y = 12.54 - 1.847ln(ttf)$	Eq. (29)
		$ln(ttf) = 0.947ln(I) + 8.835V^{0.32}$	Eq. (30)

Once the probit value has been calculated it is then possible to relate this to a fraction or percentage via tables, or a graph or a calculation such that

$$\boldsymbol{P = 0.5\left[1 + \frac{Y-5}{|Y-5|} erf\left(\frac{|Y-5|}{\sqrt{2}}\right)\right]} \qquad \textbf{Eq. (31)}$$

Bayesian Network

In the domino effect, the Bayesian network can be used to analyse the accident scenarios and study the influence degree of each factor according to the conditional probability. The Bayes' theorem provides a simple method to calculate the probability from the Equation (32).

$$\boldsymbol{P(B/A) = \frac{P(A/B)P(B)}{P(A)}} \qquad \textbf{Eq. (32)}$$

Case study

A terminal initially designed to consist of eight crude oil floating roof storage tanks used for the storage and exportation of crude oil. Two tanks (T 1-2 and T 1-8) have been changed to be used for the storage of Kerosene. The storage tanks were made up of carbon steel material with dimensions of 58m diameter and 17m height. Each two-storage tank was provided with a secondary containment dike. The terminal layout plan is shown in Figure (3).

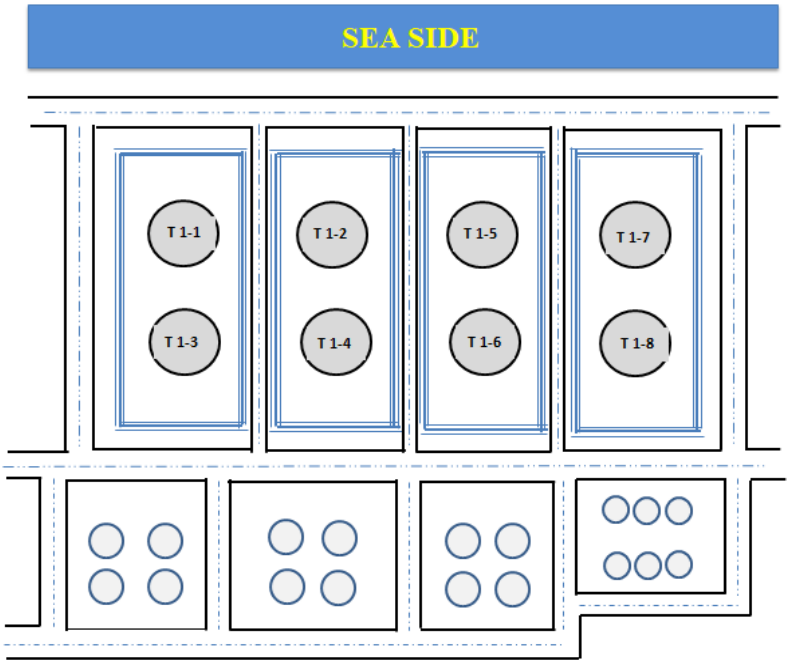

Figure (3): Schematic Diagram of the Layout of the Floating Roof Storage Tanks.

Table (5) summarizes the floating roof main parameters.

Table (5): Floating Roof Storage Tanks Main Parameters.

Description	TANK NUMBER	
	T(1-1) T(1-3) T (1-4) T(1-5) T(1-6) T(1-7)	T(1-2) & T(1-8)
Tank type	Vertical cylindrical	Vertical cylindrical
Roof type	Floating pontoon	Floating pontoon
Bottom type	Cone up	Cone up
Nominal Diameter (m)	57.9	57.9
Total shell height (m)	17	17
Type of product	Crude oil	Kerosene
Nominal capacity (m3)	44663	44663
Corresp. Height (m)	17	17
Usable capacity (m3)	41521.714	41521.714
Corresp. Height (m)	16.5	16.5
Density (kg/L)	0.8	0.8
Roof legs Operational position (m)	2.17	2.17

Table (6) summarizes the flammable material parameters.

Table (6): Flammable Material Parameters.

	Crude oil	**Kerosene**
Boiling temperature (K)	810.93	423
Density (kg/m^3)	800	780
Heat of combustion (kJ/kg)	42600	43200
Heat of vaporization (kJ/kg)	366	251
Heat capacity $(kJ/kg\ K)$	2.2	2.1

Table (7) summarizes the metrological parameters.

Table (7): Metrological Parameters.

Relative humidity %	70
Ambient temperature (K)	298
Wind speed $(m\ sec^{-1})$	8

Estimation of Thermal Radiation

This work is based on a hypothetical fire occurred on one of the floating roof storage tanks in the terminal. In order to estimate the thermal radiation which results in from the fire in one of the tanks, some assumptions have been made:

1. Fire incident occurred in a floating roof crude oil storage tank T 1-1. Therefore, the storage tank T 1-1 was selected as the primary tank for the study.
2. The prevailing wind condition is North West (NW). T 1-1 is upwind for the other storage tanks.
3. The fire is limited to tank roof.
4. The domino effect calculations are limited to four tanks only

Figure (4) shows the layout of the floating roof tanks and the distance between tanks and the dike.

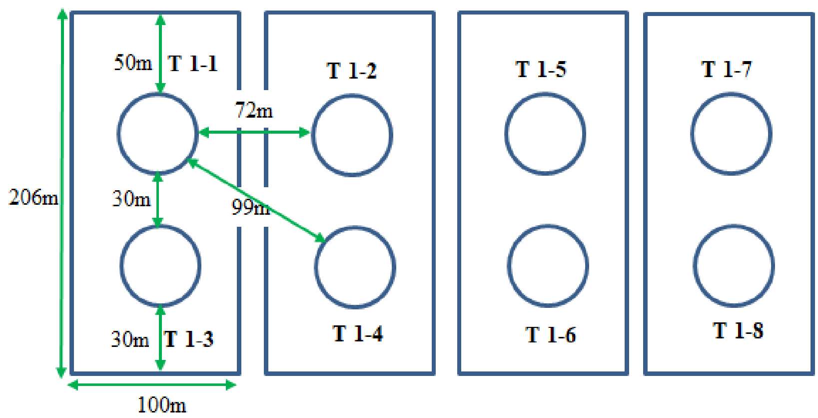

Figure (4): Layout of the Floating Roof Tanks.

Results and Discussion

Point source and solid plume models have been used for the estimation of the thermal radiation from T 1-1 to T1-2, T 1-3, T 1-4 and from T 1-2 to T 1-4 and finally from T 1-3 to T 1-4. Burning rate, pool diameter and flame length are parameters which are not affected by the choice of the radiation model. The flame length of Thomas was found higher than that of Heskestad therefore it was selected for the calculations of the distance to the receptor. Table (8) summarises the output parameters. Figure (5) and (6) show the geometry of the pool fire for point source and cylindrical solid plume models.

Table (8): Numerical Output Parameters.

Parameter		Crude oil	Kerosene
Burning rate, m_B, $(m^{-2}S^{-1})$		0.045	0.039
Diameter of the pool, D, (m)		57.9	57.9
Area of the Pool, A, m^2)		2631.64	2631.64
Flame surface area, A_f (m^2)		5623.059	7901.288
Flame length, L (m)	Thomas (1963) (no wind)	47.43	43.46
	Heskestad (2002) (no wind)	39	34

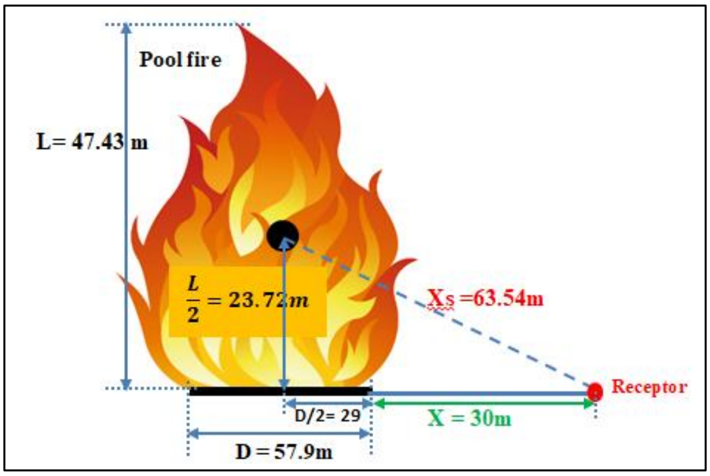

Figure (5): The Geometry of the Pool Fire in Still Air Conditions for Point Source Model.

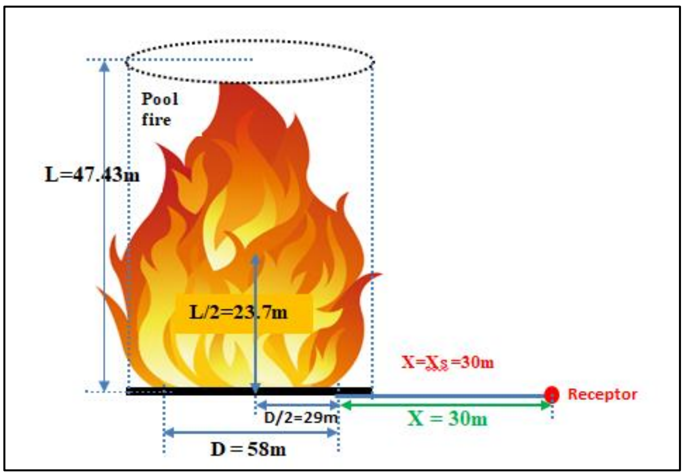

Figure (6): Cylindrical Pool Fire in Still Air Conditions for Solid Plume Model.

The point source and solid plume equations in Figure (2) have been used for the estimation of the distance from the flame source to the receptor, the energy radiated by the source, the atmospheric transmissivity, the geometric view factor and the heat flux. Table (9) summarizes the point and solid plum model results.

Table (9): The Point and Solid Plum Model Results.

Thermal radiation from crude oil storage tank (T 1-1) to Kerosene storage tank (T 1-2).			
Point source model		**Solid plume model**	
Distance from the point source to the receptor, $x_{S,}$ (m)	103.8	Distance from the flame surface to the receptor, x (m)	72.1
Energy radiated by the source, Q (kJ/Sec)	1765698.858	Surface Emitted Power, SEP $(Js^{-1}m^{-2})$	56.952
Atmospheric transmissivity, τ_a	0.716	Atmospheric transmissivity, τ_a,(m^{-2})	0.74
Geometric view factor, F_P (m^{-2})	0.0000731	Geometric view factor, F_{21}, (m^{-2})	0.07
Heat flux at Distance, E_r (kWm^{-2})	9.34	Heat flux at Distance, Er (kWm^{-2})	2.95
Thermal radiation from crude oil storage tank (T 1-1) to crude oil storage tank (T 1-3).			
Point source model	**Solid plume model**		
Distance from the point source to the receptor, $x_{S,}$ (m)	63.54	Distance from the flame surface to the receptor, x (m)	30
Energy radiated by the source, Q (kJ S^{-1})	1765968.858	Surface Emitted Power, SEP $(Js^{-1}m^{-2})$	56.95 2
Atmospheric transmissivity, τ_a	0.748	Atmospheric transmissivity, τ_a,(m^{-2})	0.801
Geometric view factor, F_P (m^{-2})	0.00001972	Geometric view factor, F_{21}, (m^{-2})	0.19
Heat flux at Distance, E_r (kWm^{-2})	26.046	Heat flux at Distance, Er (kWm^{-2})	8.667
Thermal radiation from crude oil storage tank (T 1-1) to crude oil storage tank (T 1-4)			
Point source model	**Solid plume model**		
Distance from the point source to the receptor, $x_{S,}$ (m)	130.1	Distance from the flame surface to the receptor, x (m)	99
Energy radiated by the source, Q (kJ S^{-1})	1765698.858	Surface Emitted Power, SEP $(Js^{-1}m^{-2})$	56.95 2
Atmospheric transmissivity, τ_a	0.702	Atmospheric transmissivity, τ_a,(m^{-2})	0.719
Geometric view factor, F_P (m^{-2})	0.000047	Geometric view factor, F_{21}, (m^{-2})	0.04
Heat flux at Distance, E_r (kWm^{-2})	5.8	Heat flux at Distance, Er (kWm^{-2})	1.6
Thermal radiation from Kerosene storage tank (T 1-2) to crude oil storage tank (T 1-4)			
Point source model	**Solid plume model**		

Distance from the point source to the receptor, $x_{S,}$ (m)	62.84	Distance from the flame surface to the receptor, x (m)	30
Energy radiated by the source, Q (MJ S^{-1})	1551825.475	Surface Emitted Power, SEP $(Js^{-1}m^{-2})$	55.28
Atmospheric transmissivity, τ_a	0.749	Atmospheric transmissivity, τ_a,(m^{-2})	0.801
Geometric view factor, F_P (m^{-2})	0.0000201	Geometric view factor, F_{21}, (m^{-2})	0.18
Heat flux at Distance, E_r (kWm^{-2})	23.36	Heat flux at Distance, Er (kWm^{-2})	7.97
Thermal radiation from crude oil storage tank (T 1-3) to crude oil storage tank (T 1-4)			
The results is the same as from crude oil storage tank (T 1-1) to crude oil storage tank (T 1-3)			

From Table (9) the point source model predicts higher heat flux at receptor than solid plume model. This overestimation of heat flux leads to considerably conservative prediction of the thermal effect on receptor. The thermal radiation which is estimated by point source model is higher than that found from solid plume model. Although the solid plume model is more realistic than the point source model thermal radiation however the point source is considered worst case scenario and it will be used for comparison with the thermal radiation criteria. The thermal radiation which results in from tank T 1-1 to tank T 1-3 (26.646kWm^{-2}) is higher than the threshold heat radiation level (15 kWm^{-2}) and less than (31 kWm^{-2}) the heat radiation level of the equipment damage. The floating roof storage tanks are provided with automatic firefighting system which can be actuated immediately in addition to the emergency response team.

The thermal radiation from crude oil storage tank T 1-1 to kerosene storage tank T 1-2 is 9.34 kWm^{-2} which is less than the threshold heat radiation level (15 kWm^{-2}). Therefore, the tank T 1-2 does not affect by the heat radiation from tank T 1-1.

The thermal radiation from kerosene storage tank T 1-2 to crude oil storage tank T 1-4 is 23.36kWm^{-2} which is higher than the threshold heat radiation level (15 kWm^{-2}) and less than (31 kWm^{-2}) the heat radiation level of the equipment damage.

The thermal radiation from crude oil storage tank T 1-3 to crude oil storage tank T 1-4 is equal to the thermal radiation of tank T 1-1 to tank T 1-2 which is9.34 $kJ/m^2\ sec$. The thermal radiation is less than the threshold heat radiation level (15 kWm^{-2}). Therefore, the tank T 1-4 does not affect by the heat radiation from tank T 1-3.

Comparison of Tanks Safe Separation Distances

The tank farm consists of eight floating roof storage tanks. The diameter of the storage tank is 58m. Each two floating roof storage tanks are surrounded with an independent dike. The separation distance between each two tanks in one dike is 30m. The estimated safe distance between tanks by using point source model was found to be 24m. Table (10) summarizes a comparison of the actual tanks safe separation distance with the codes and the estimated safe distances.

Table (10): Comparison of the Estimated Distance with the Codes.

Codes and Models	Tank Spacing (Shell-to-Shell) (m)
Marsh Companies	58
HSE – 176	15
The NFPA-30 code	19.33
KLM Technology Group	17.4
The Oil Industry Safety Directorate (OISD)	29
China code GB 50,074-2014	23.2
Taiwan's regulations	29
Point source model	24

It has been noted that the storage tanks separation distance is as OISD and Taiwan's regulations. Marsh Companies provides the most conservative estimates whereas the least conservative safe separation distances were obtained using HSE-176.

Estimation of Domino Effect

The domino effect is estimated based on the thermal radiation and the probability analysis. The thermal radiation which resulted in from the source tank (primary tank) should be compared with a criterion to verify that the thermal radiation has an impact on the secondary and tertiary tanks which might result in domino effect. The threshold quantity 15 kW/m^2 was selected as the criterion. Table (11) summarizes the heat radiation flux between the source and the targeted tanks (T 1-1) to (T 1-2, (T 1-1) to (T 1-3), and (T 1-1) to (T 1-4).

Table (11): The Heat Radiation Flux to Receiver.

Tank to tank	Distance (m)	Heat radiation flux kW/m^2	Comparison of heat radiation with criterion
(T 1-1) to (T 1-2)	72.1	9.34	$E_r < 15$
(T 1-1) to (T 1-3)	30	26	$15 < Er < 31$

(T 1-1) to (T 1-4)	99	5.8	$E_r < 15$
(T 1-2) to (T 1-4)	30	23.36	$15 < Er < 31$
(T 1-3) to (T 1-4)	72.1	9.34	$E_r < 15$

Figure (7) shows the Bayesian network based on domino effect

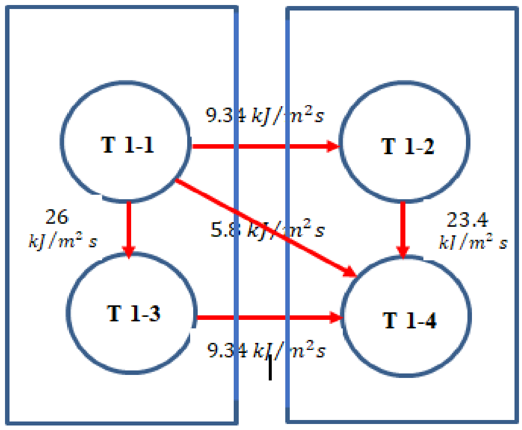

Figure (7): Bayesian Network Based on Domino Effect.

It has been noted that the thermal radiation between tanks T 1-1 to T 1-2, and T 1-1 to T 1-4, and T 1-3 to T 1-4 are less than the threshold heat level. Therefore, the target tanks are not affected by thermal radiation and will not result in domino effect. The thermal radiation between tanks T 1-1 to T 1-3 and T 1-2 to T 1-4 exceed the threshold heat quantity and less than the steel deformation heat quantity. Therefore, the targeted tanks might be subjected to domino effect if the automatic firefighting system and emergency response team do not activate.

Bayesian Network

It was assumed that a pool fire occurred in tank T 1-1. The tank T 1-1 is the primary pool fire, which the most likely Bayesian network based on domino effect according to spacing of tanks. Figure (8) shows the Bayesian network.

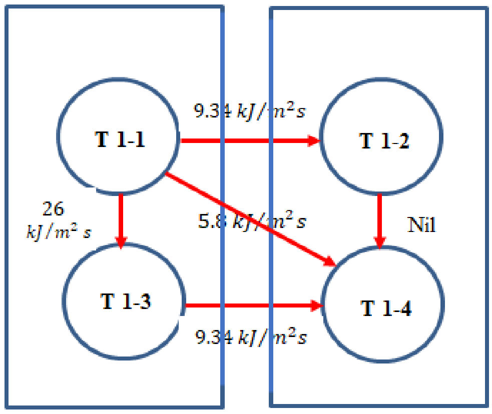

Figure (8): Bayesian Network Based on Domino Effect.

The domino effect was analysed according to the pool fire consequence model and the probability model in tank farm. Therefore, the heat radiation flux and the accident escalation probability received by the target tanks are shown in Table (12).

Table (12): The Heat Radiation Flux to Receiver and the Escalation Probability.

Tank to tank	Distance between tanks (m)	Heat radiation flux kW/m^2	Escalation probability
(T 1-1) to (T 1-2)	72.1	9.34	-
(T 1-1) to (T 1-3)	30	26	0.04
(T 1-1) to (T 1-4)	99	5.8	-
(T 1-2) to (T 1-4)	30	-	-
(T 1-3) to (T 1-4)	72.1	9.34	-

Comparing the heat radiation threshold with the heat radiation flux received by the targets, the thermal radiation from tank (T 1-1) to tank (T 1-3) is denoted E_{r13} . $E_{r13} = 26.046\, kW/m^2 > 15\, kW/m^2$ thus tanks T 1-3 is selected as secondary unit. The thermal radiation from tank (T 1-1) to tank (T 1-2) is E_{r12}. The thermal radiation from tank (T 1-3) to tank (T 1-4) is E_{r34} . $E_{r12} = E_{r34} = 9.34\, kW/m^2 < 15\, kW/m^2$. Therefore, tank T 1-2 was not selected as secondary unit. The thermal radiation from tank (T 1-1) to tank (T 1-4) $E_{r14} = 5.81\, kW/m^2$.

The escalation probability of accidents for tanks (T 1-1) to (T1-3) was estimated to be 0.04. The escalation probabilities of tanks (T 1-1) to (T 1-2) and (T 1-3) to tank (T 1-4) are 0. Therefore, tank T 1-4 cannot be chosen as the tertiary unit.

The received radiation fluxes of tank T 1-4 from both tanks T 1-1 ($5.81\, kW/m^2$) and T 1-2 (0) are $5.81\, kW/m^2$ which is less than the threshold amount $15\, kW/m^2$ $(E_{r4} = E_{r14} + E_{r24})$ respectively.

It can be seen that the received radiation fluxes of tank T 1-4 from tanks T 1-1 $5.81\, kW/m^2$ and T 3-4 are $9.34\, kW/m^2$ are $15.15\, kW/m^2$ $(E_{r4} = E_{r14} + E_{r34})$ respectively. Therefore, that total thermal radiation received by E_{r4}

$$\boldsymbol{E_{r4} = E_{r14} + E_{r24} + E_{r34}} \qquad \textbf{Eq. (33)}$$

$$\boldsymbol{E_{r4} = 5.81 + 0 + 9.34 = 15.15\, kW/m^2} \qquad \textbf{Eq. (34)}$$

E_{r4} does not exceed the heat radiation threshold quantity. It is obvious that when there are multiple thermal radiation fields, the possibility of an accident has increased. Figure (9) shows the thermal radiation received by tank T 1-4.

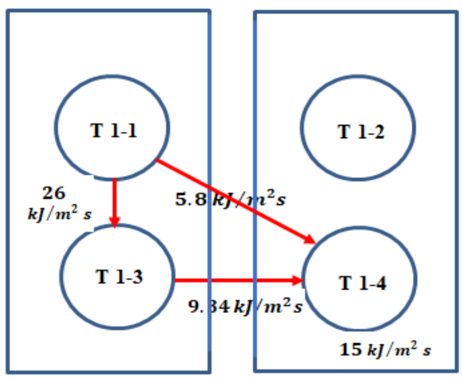

Figure (9): Thermal Radiation Received by Tank T 1-4.

The probability of the domino accident of storage tank T 1-3 was estimated through Bayes' theorem and it was found to be1.6×10^{-8}.

Conclusions

The pool fire in crude oil storage tank, the thermal radiation semi empirical models, safe separation distance between storage tanks, and thermal radiation consequences and escalation probability of the domino effect in pool fire have been summarized. Based on the above theories and models, the influencing of thermal radiation and domino effect that caused by pool fire in tank farm are analysed, especially the most important of these is the thermal radiation flux impacting on a receiver. The study has been focused on 2×2 storage tanks in the tank farm consists of eight floating roof storage tanks. When the poo fire occurs in one tank, the adjacent tank in the same dike is affected while the tanks in the other dike have not been affected. Although the farther away tank is not affected; however, when there are multiple thermal radiation fields, the possibility of domino accident is almost occurred.

The occurrence probability of the domino accident at the first level was found to be1.6×10^{-8}. The safe separation distance between tanks played vital role in the prevention of the domino effect.

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