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Evaluation of the Domino Effect Caused by Pool Fires 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 resulting from a pool fire in a tank farm consisting of eight large floating-roof storage tanks, with a focus on four specific tanks. A crude oil storage tank was selected as the primary tank (source tank). Point source and plume solid models were used to estimate 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 result in a domino effect; however, the thermal radiation from the source tank alone does not reach the threshold level for the tanks in the other dike. Additionally, it was found that the thermal radiation from both the primary and secondary tanks just reaches the threshold level for the farther-away tank in the other dike. The domino effect occurs provided that the firefighting system is not activated and the emergency response team does not intervene within ten minutes.

تقييم تأثير الدومينو من حريق حوض خزان نفط على خز انات النفط الخام

ابراهيم شلوف، نهى كرير، وسالم صاكال

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الكلمات المفتاحية:
خران النفط
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الاشعاع الحراري
تاتير الدومينو

الملخص

المنشئات الصناعية ذات الدرجة العالية من الخطورة مثل الحقول النفطيه ومصافي تكرير النفط ومجمعات البتروكيماويات وموانى تصدير النفط تستخدم خزانات ذات احجام كبيره لتخزين النفط الخام ومشتقاته. تعد حرائق الحوض ألاكثر شيوعا من بين انواع حرائق خزانات النفط. هذا المقال يهدف الي دراسة حرائق الحوض في مصب نفطي يتكون من ثمانية خزانات كبيره ذات الاسطح العايمه. واجريت الحسابا ت على اربع خزانانات وذلك لدراسة امكانية حدوت تاتير الدومينو من حريق الحوض باحدى الخزنات. لقد ثم اختيار خزان نفط خام كمصدر اولي وباستخدام نمادج النقطه والعمود المصمت لحساب الاشعاع الحراري ومقارنتها بالحد الادنى لمستوى الاشعاع الذي يمكن ان يسبب تاتير الدومينو. تبين ان الاشعاع الحراري الناتج من خزان المصدر الي الخزان الثاني في نفس الحوض يتجاوز الحد الادنى للاشعاع الحراري وينتج عنه تاتيرات الدومينو وليس للاشعاع الحراري اي تاتير من خزان المصدر على الخزانات في الحوض المجاور ولكن تبين ان مجموع الاشعاع الحراري من خزان المصدر والخزان الثانوي يصل الى الحد الادنى لحدوت الدمينو. ولا يحدت الدومينو اذا تدخلت اجهزة الاطفاء الاليه في الوقت المناسب او تدخل فريق الطواري واطفاء الحريق خلال عشرة دقائق.

1. Introduction

Major hazard installations (MHIs), such as refineries, petrochemical plants, and terminals, usually use large-capacity storage tanks for storing crude oil and by-products. The major hazards resulting from the operation of MHIs include fire, explosion, and toxic release [1]. The world has witnessed many tank fire incidents [2]. Pool fire is one of the most common types of fire accidents in the chemical process industry (CPI). Buncefield, UK (2005), Sitapura, India (2009), and Puerto Rico, USA (2009) are examples of very large and persistent pool fires that occurred in tank farms [3]. The thermal radiation from pool fires might affect adjacent storage tanks, resulting in a domino effect. The domino effect describes a chain of accidents in which a primary accident escalates into higher-order accidents. Such accident

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scenarios are more likely to cause massive damage to people, assets, and the environment than stand-alone accidents. A domino effect occurs when a minor accident triggers a sequence of events that causes damage over a larger area and leads to severe consequences. An accident can be categorized as a domino effect if three concepts are involved: (1) a "primary" event that occurs in a specific unit, (2) the propagation of the accident to one or more units, triggering "secondary" accidents as a result of the primary event, and (3) an "escalation" effect that results in an overall increase in impacts, with secondary accidents being more severe than the primary one [4]. There are two main patterns identified for propagation and escalation: (1) direct escalation and (2) indirect escalation.

Previous studies indicate that the frequency of domino effects has increased in the chemical and process industries in recent decades. 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. Pool fires account for 44 percent of all accident scenarios that escalate to a domino effect. 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. The possibility of a domino event caused by a pool fire may vary under different conditions [5]. As these frequent and dangerous accidents occur in the chemical industry, pool fires are often blamed as one of the primary accidents triggering domino events [6]. A historical analysis of 261 accidents involving domino effects showed that storage areas are the most probable initiators of a domino effect [7]. Kadri also highlighted that past domino accidents reveal that the most typical primary incidents in a domino effect sequence are explosions (57%), followed by fires (43%). In Taiwan, it was noted that some storage tank fires or explosions lead to more disasters due to insufficient safety distances between storage sites and adjacent areas [8]. This technical article aims to present an overview of the evaluation of domino effects resulting from pool fires in large-capacity crude oil storage tanks through a case study.

Thermal Radiation Estimation

Several models have been proposed in the literature to estimate thermal radiation and its effects [9][10]. Semi-empirical models are highlighted as 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 consist of several submodels, as schematically shown in Figure 1.

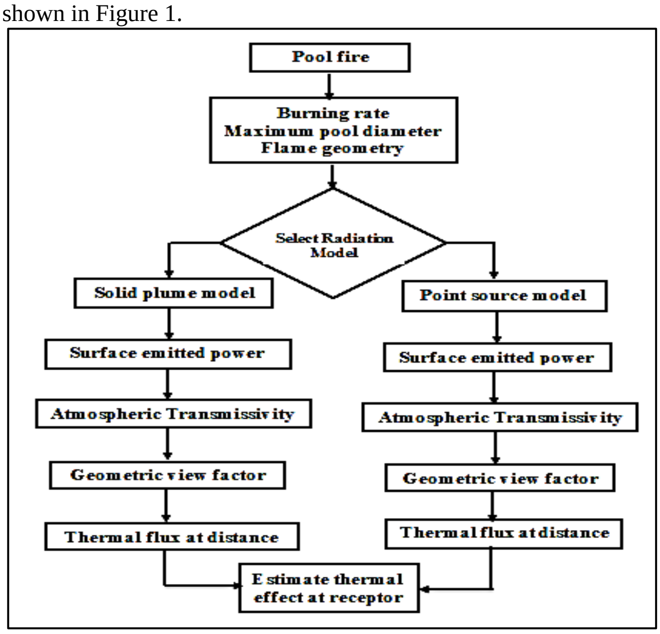

Fig 1: Pool fire models schematic diagram.

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 [11], Thomas and Moorhouse [12]. 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= $0.23Q^{2/5}$ - 1.02D Eq. (2)	No
Thomas (1963)	$L/D = 55\left[m_B/\rho\sqrt{gD}\right]^{0.67} u^{*0.21}$ Eq. (3) $cos\theta = 0.7[u_W/(gm_BD/\rho_a)]$ Eq. (4) $u^* = u_W/(gm_BD/\rho_V)^{1/3}$ 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.

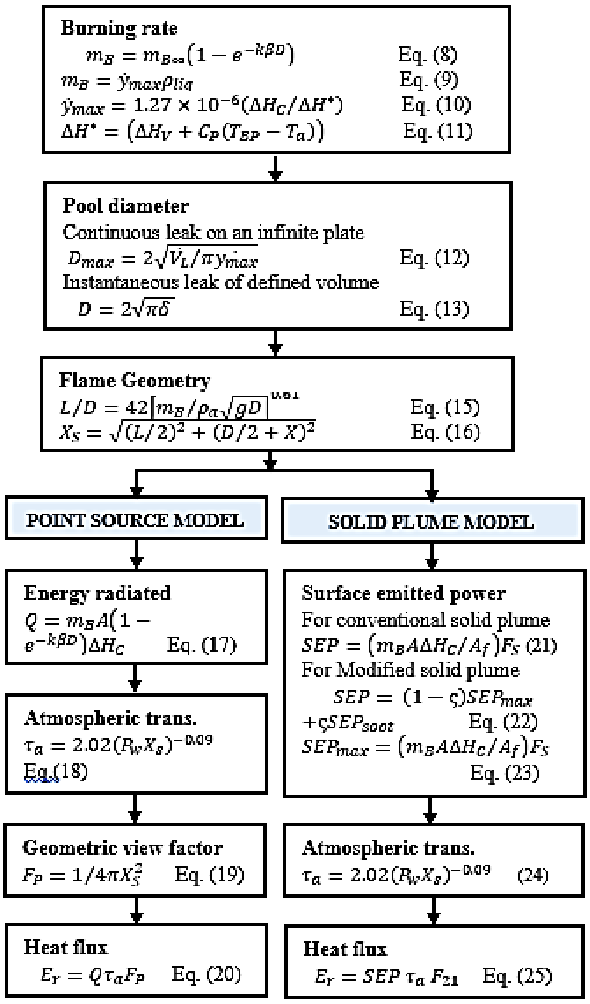

Fig. 2: Point source models steps and equations

2. 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 [13]	1 x the diameter of the largest tank with an absolute minimum of 15 meters.
HSE – 176 [13]	15 m for tanks diameter above 45 m diameter.
The NFPA-30 code [13]	1/6 sum of adjacent tank diameters
KLM Technology Group [13]	Half the diameter of the larger tank, but not less than 10 m and need not be more than15m.
OISD [13]	Tanks with diameter exceeding 50 m, (D + d)/4
China code GB 50,074-2014 [14]	0.4 diameter
Taiwan's regulations [8]	The spacing shall be one-sixth (1/6) of the sum of the diameter of two abutted tanks

3. 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 [15]. It was highlighted that a heat flux of $5 kW/m^2$ is commonly used as a criterion to specify exclusion zones for emergency personnel [16]. The Department of Housing and Urban (HUD) has established radiation flux levels of $31.5\, kW/m^2$ for buildings and $1.4 kW/m^2$ for people as guidelines in determining an Acceptable Separation Distance (ASD) between a fire consuming combustible liquids or gases and nearby structures and people [17]. 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 [14].

Table 3: Level of heat flux effect on people 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

4. Mechanism of domino effect in pool fire

4.1. Characteristics

It was found that the domino effect has at least the following three characteristics [14]

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.

4.2. 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

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

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	$Y = 12.54 - 1.847 ln(ttf)$ Eq. (27) $ln(ttf) = -1.128 ln(I) - 2.667 \times 10^{-5} V + 9.887$ Eq. (28)
	Pressurized	$Y = 12.54 - 1.847 ln(ttf)$ Eq. (29) $ln(ttf) = 0.947 ln(I) + 8.835 V^{0.32}$ 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

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

4.3. 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).

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

5. 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.

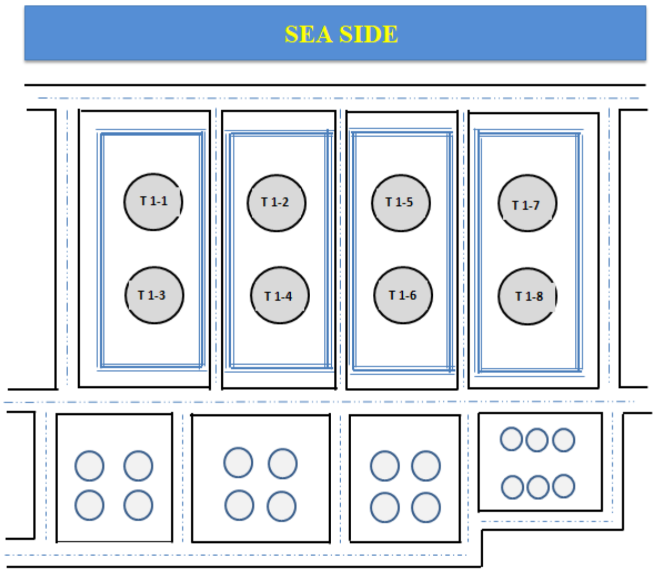

Fig. 3: Schematic diagram of the layout of the floating roof storage tanks

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

6. 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.

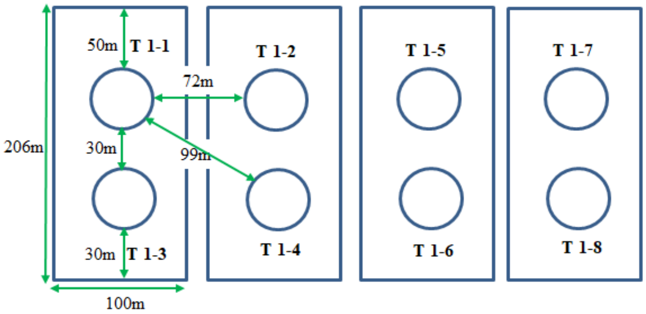

Fig. 4: Layout of the floating roof tanks

7. 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

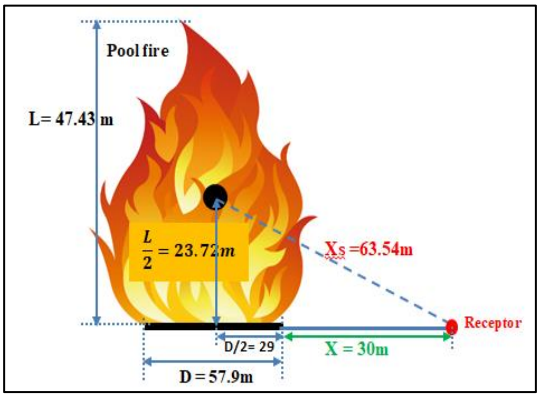

Fig. 5: The geometry of the pool fire in still air conditions for point source model

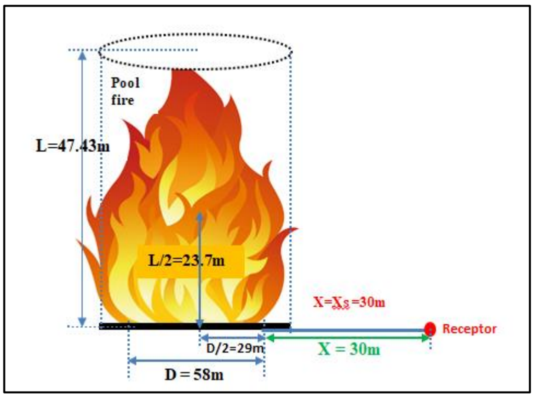

Fig. 6: Cylindrical pool fire in still air conditions for solid plume model

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 $(Js^{-1}m^{-2})$	56.952
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 $(Js^{-1}m^{-2})$	56.952
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 are 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 (26.646kW m^{-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.

7.1. 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.

7.2. 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

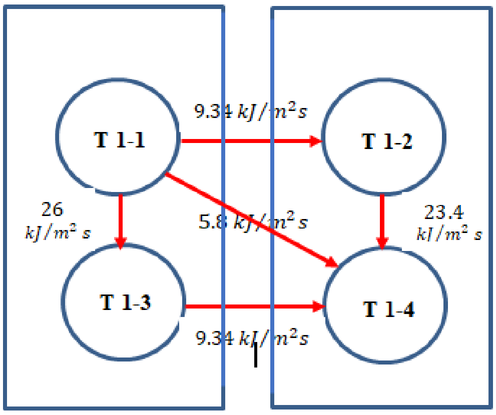

Fig. 7: Bayesian network based on domino effect

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.

7.3. 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.

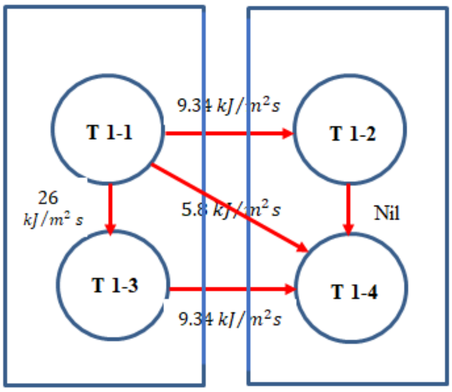

Fig. 8: Bayesian network based on domino effect

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) isE_{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}

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

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

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.

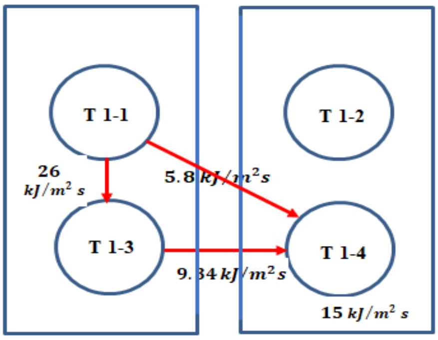

Fig. 9: Thermal radiation received by tank T 1-4

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}.

8. Conclusions

The pool fire in crude oil storage tanks, the thermal radiation semi-empirical models, safe separation distances between storage tanks, and the consequences of thermal radiation along with the escalation probability of the domino effect in pool fires have been summarized. Based on these theories and models, the influence of thermal radiation and the domino effect caused by pool fires in tank farms is analyzed, with a particular focus on the impact of thermal radiation flux on a receiver.
The study focused on a 2×2 configuration of storage tanks within a tank farm consisting of eight floating-roof storage tanks. When a pool fire occurs in one tank, the adjacent tank in the same dike is affected, while the tanks in the other dike are not impacted. Although the farther-away tanks are not affected, the presence of multiple thermal radiation fields significantly increases the likelihood of a domino accident. The occurrence probability of a domino accident at the first level was found to be 1.6×10−81.6 \times 10^{-8}1.6×10−8.

The safe separation distance between tanks plays a vital role in preventing the domino effect.

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