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Evaluation of Thermal Radiation Hazards for Crude Oil Storage Tank Pool Fire

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Abstract

Major hazard Installation (MHIs) such as refineries, petrochemical plants and terminals use storage tanks for storing of crude oil and by products. Pool fire is one of the most common types of fire accidents in storage tanks. This technical article aims to present an overview on the estimation of thermal radiation which results in from a pool fire in crude oil storage tank through a case study. Two pool fire scenarios were considered for the study of thermal radiation, fire in the storage tank and fire in the tank and its bund. Point source model and solid plume model (conventional and modified) were used for estimation of thermal radiation. The thermal radiations which are resulted in from point source model in both scenarios were found to be exceeding the permissible targeted criteria level for structure. Although the thermal radiation from solid plume was found to be below the permissible targeted criteria level for structure, however the operators and emergency responders are at high risk of thermal radiation.

Key words: Crude Oil**,** Storage Tank**,** Pool Fire, Thermal Radiation.

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تقييم مخاطر الإشعاع الحراري لحريق حوض خزان النفط الخام

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الملخص:

المنشئات الصناعية ذات الدرجة العالية من الخطورة مثل مصافي تكرير النفط ومجمعات البتروكيماويات وموانى تصدير النفط تستخدم خزنات ذات احجام كبيره لتخزين النفط الخام ومشتقاته. تعد حرائق الحوض الأكثر شيوعا فى حرائق خزانات النفط. هذا المقال يهدف الى تقديم ملخص يوضح تقييم مخاطر الاشعاع الحراري الناتج من حرائق بخزانات النفط الخام وذلك بدراسة لخزانات نفط خام بميناء نفطي. لقد تمت دراسة حرائق الحوض في حالتين في خزان نفط وفي الخزان مع السد المحيط بالخزان. لقد استخدمت نماذج تمثيل اللهب كنقطه ونماذج تمثيل اللهب كعمود مصمت (الطريقة التقليدية والمعدّلة) لحساب الاشعاع الحراري. لقد لوحظ ان كمية الاشعاع الحراري باستخدام نماذج النقطة في كلتا الحالتين يتجاوز الحد المسموح به للتأثير على العاملين والاصول والمعدات. وبالرغم من ان حساب كمية الاشعاع الحراري باستخدام نماذج العمود المصمت اقل من الحد المسموح به للمعدات الا انه يعرّض العاملين وفرق الانقاذ لخطر الاشعاع الحراري.

الكلمات الدالة: الزيت الخام، خزان النفط، حريق الحوض، الاشعاع الحراري.

Introduction

Major hazard Installation (MHIs) such as refineries, petrochemical plants and terminals use 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. Of these three, fire is the most common (Daniel A. Crowel and Joseph F. Louvar, 2002). MHIs are usually use large capacity storage tanks

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for storing of crude oil and by products. It has been highlighted that 480 tank fire incidents have been identified dated from 1951 to 2003. The types of fires that were identified range from minor incidents, such as partial rim seal fires, to fires more or less involving the complete oil storage facility (Henry Persson and Anders Lönnermark, 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 (Omran Ahmadi et al. 2019). Pool fires can often take place due to the accidental leakages of hydrocarbon fuel during storage and transportation, and they may induce a chain of events that amplify the accident, namely domino effect. A survey on 224 typical process industry accidents involving domino effect shows that 43% cases were initiated by fires of which 80% were pool fires (Kuibin Zhou and Xiuzhen Wang, 2019). The radiant heat emitted by flame usually plays a key role in ignition, fire spread and even explosion threatening the occupants and facilities nearby. Thus, it is essential to investigate the thermal radiation of pool fire. Point source and solid flame models are applied for pool fire in MHIs bulk storage of hydrocarbons (Rahul Agriwal, and Nisha Kushwaha, 2021). Dili O. Nwabueze (2016) 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. Radiation level of $5kW/m^2$ and above is capable of causing second degree burns to people within 60 seconds of exposure and impairs escape ability, while radiation level of $10\,kW/m^2$ and above would be potentially fatal with 60 seconds. Anay Luketa (2022) highlighted that a heat flux of $5kW/m^2$ is commonly used as a criterion to specify exclusion zones for emergency personnel. The Department of Housing and Urban (HUD) has established radiation flux levels of $31.5kW/m^2$ for buildings and $1.4kW/m^2$

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for people as guidelines in determining an Acceptable Separation Distance (ASD) (Kevin B. McGrattan et al., 2000).
This technical article aims to present an overview on the estimation of thermal radiation which might be resulted in from a pool fire in crude oil storage tanks. Point source model and solid plume conventional and modified radiation models were used for the estimation of the thermal radiation. Two fire scenarios were considered for the estimation(i) fire in the storage tank (ii) fire in the tank and bund.

Storage tank fire incidents

Crude oil storage tank has two kinds, fixed roof tank and floating roof tank. Floating roof tank is the optimum selection for storing larger quantities of crude oil. In the construction of crude oil storage tank, the most common standard in the world is US standard API 650, other standards EU has BS2654, Chinese has GB50341, and Japanese has JIS B8501 (Zoe Nivolianitou et al., 2012). The failure of tank can have several undesirable effects such as endangering personnel, affecting the environment and interrupting the operator's business. The world has seen many tank fire incidents. A review of 242 storage tank accidents from 1960 to 2003 highlighted that accidents occurred more frequently at petroleum refineries, with 116 such cases (about 47.9%). The second most frequent accidents involved import/export terminals, with 64 cases (26%). Fire is the most common type of accident encountered in CPI. ZHANG Miao et al., (2014) highlighted that a survey of accidents taken from major hazards incident data concluded that approximately 42% of all accidents in CPI involve pool fires. Large scale pool fires are often disastrous and difficult to control. The fire that broke out in Jaipur, India in 2009 is a good example of a disastrous pool fire. The tank fire scenario depends upon the type of construction of the tank roof. Fires in floating roof tanks can be rim seal fire, spill on roof fire, full surface fire, pool fire, and pontoon explosion (Ali Sari, 2016). The most common failure causes of fixed/cone and floating roof tanks are summarized by John M. Lieb (2001), Zoe Nivolianitou et al.

(2012) and Ken Donaghey (2018). The storage tanks 2 and 12 at Ras Lanuf terminal were exposed to catastrophic damage due to the armed assault. This has resulted in 400,000 barrel reduction of crude oil storage capacity (Gary Dixion, 2018).

Pool fire models

It was highlighted that in order to estimate the heat flux and its effects, many models have been introduced in literature (Zuzana Labovská and Juraj Labovský, 2016), (Roberto Bubbicoa et al., 2016). It was also 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.

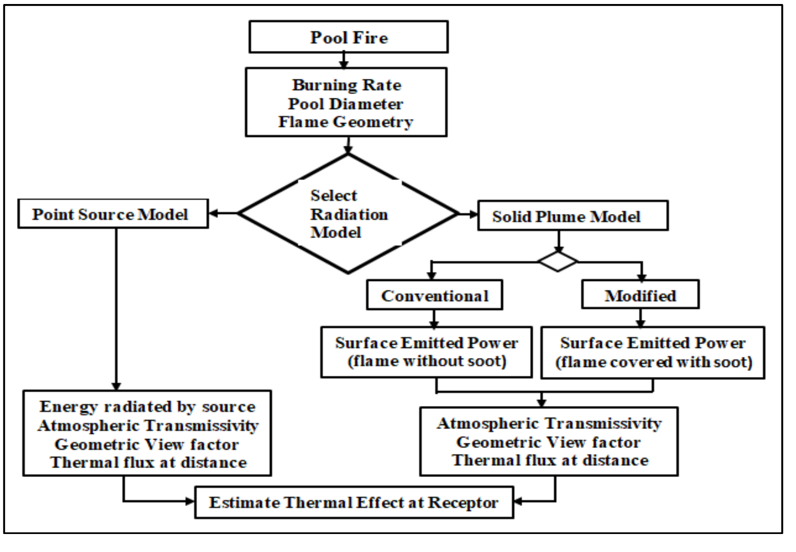

Figure 1. Pool fire models schematic diagram.

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 diameter of the pool fire depends

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upon the release mode, release quantity (or rate), and burning rate. Circular pools are normally assumed; when dikes lead to square or rectangular pool shapes, an equivalent diameter can be used (Sivasubramanian V. and Naveen S., 2014). 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 Gunnar (2002), Thomas and Moorhouse (Ufuah, E. and Bailey, C, 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 speed
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)	$L/D = 55\left[m_B/\rho\sqrt{gD}\right]^{0.67} u^{*0.21}$ 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
Binding-Pritchard (1992)	$L/D = 10.615\left[m_B/\rho\sqrt{gD}\right]^{0.305} u^{*-0.03}$ Eq. (7)	Yes

The emissive power of a flame can be modeled based on the point source theory and the surface emitter theory. Ufuah, E. and Bailey, C, (2011) highlighted that for large diameter soot-producing hydrocarbon pool fires, copious amount of soot can be produced thereby creating the tendency for the unburnt soot to escape from the flame. The soot then congregates and forms a film around the flame surface, thus limiting the radiation to external structures. Figure 2 represents the classical and the modified cylindrical flame models for pool fires by the point source and surface emitter concepts.

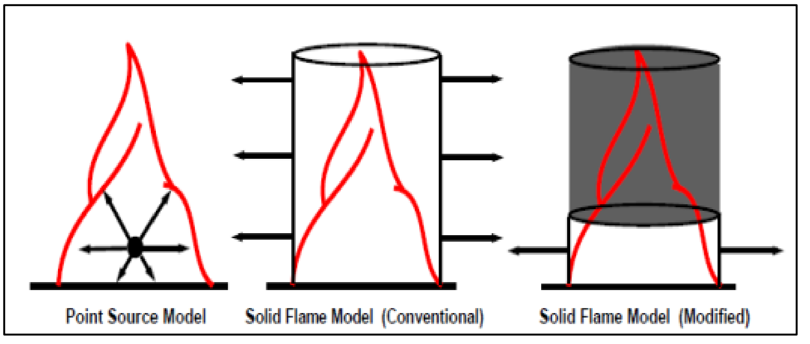

Figure 2. Thermal radiation models

Atmospheric transmissivity accounts for the emitted radiation being partly absorbed by air between the flame and the receptor. Determination of the heat flux at a distance is dependent on the radiation model selected. Calculation of the thermal effect on receptor can be done in two ways. At first, if the receptor distance from the flames is known, calculation is straightforward. On the other hand, it is more useful to know the distance from the flame at which the heat flux at receptor is secure or only a low probability of fatality exists (Zuzana Labovská and Juraj Labovský, 2016). The steps and equations to estimate the heat flux by using the point source and solid flame conventional and modified models are summarized in Figure 3. Abbreviations of the article are summarized in Table 7.

Table 7. Table of Abbreviations

Symbol	Name	Symbol	Name
A	**Area of the fire** m^2	SEP_{SOOT}	**emissive power of smoke** $J\,s^{-1}m^{-2}$
A_f	**flame surface area** m^2	t	**Exposure time** s
C_p	**heat capacity** $J\,kg^{-1}K^{-1}$	T_{BP}	**boiling point temperature** K
D	**diameter of burning area** m	T_a	**ambient temperature** K
E_r	**heat flux** $kJ\,m^{-2}s^{-1}$	u^*	**nondimensional wind speed**

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F_S	fraction of the energy converted to radiation	u_W	wind speed $m\ s^{-1}$
F_P	view factor for the point source model m^{-2}	V_L	volume of flammable material m^3
F_{21}	view factor for the solid plume model	$\dot{V}_L$	volumetric leak rate $m^3 s^{-1}$
g	Acceleration of gravity ms^{-2}	x	distance of the point source to receptor m
ΔH_C	heat of combustion $J\ kg^{-1}$	x_S	distance for atmospheric transmissivity m
ΔH_V	heat of vaporization $J\ kg^{-1}$	X	distance from the flame surface to receptor m
I	incident thermal flux kWm^{-2}	$\dot{y}_{max}$	vertical rate of liquid level decreases $m\ s^{-1}$
$k\beta$	absorption extinction coefficient of the flame	Greek symbols	
L	flame length m	β	mean beam length corrector
LD_{50}	lethal dose to 50% of a population	δ	poll thickness m
m_B	burning rate $kg\ s^{-1}m^{-2}$	θ	angle of flame tilt $^\circ$
$m_{B\infty}$	fuel maximum mass loss rate $kg\ s^{-1}m^{-2}$	ρ_a	air density $kg\ m^{-3}$
P_w	partial pressure of water Pa	ρ_{liq}	fuel density $kg\ m^{-3}$
Q	energy radiated by the source $J\ s^{-1}$	ς	fraction of the surface of the pool fire flame covered by soot
SEP	surface emitted power $J\ s^{-1}m^{-2}$	τ_a	atmospheric transmissivity
SEP_{max}	maximum surface emissive power $J\ s^{-1}m^{-2}$		

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rning rate $m_B = m_{B\infty}(1 - e^{-k\beta D})$ Eq. (8)

$m_B = \dot{y}_{max}\rho_{liq}$ Eq. (9)

$\dot{y}_{max} = 1.27 \times 10^{-6}(\Delta H_C/\Delta H^*)$ Eq. (10)

$\Delta H^* = (\Delta H_V + C_P(T_{BP} - T_a))$ Eq. (11)

Pool diameter

Continuous leak on an infinite plate $D_{max} = 2\sqrt{\dot{V}_L/\pi \dot{y}_{max}}$ Eq. (12)

Instantaneous leak of defined volume $D = 2\sqrt{\pi\delta}$ Eq. (13)

Fixed pool size (equivalent diameter) $D = \sqrt{4A/\pi}$ Eq. (14)

Flame Geometry

$L/D = 42\left[m_B/\rho_a\sqrt{gD}\right]^{0.61}$ Eq. (15)

$X_S = \sqrt{(L/2)^2 + (D/2 + X)^2}$ Eq. (16)

POINT SOURCE

Energy radiated
$Q = m_B A(1 - e^{-k\beta D})\Delta H_C$ Eq. (17)

Atmospheric transmmissivity
$\tau_a = 2.02(P_w X_s)^{-0.09}$ Eq.(18)

Geometric view factor
$F_P = 1/4\pi X_\varsigma^2$ Eq. (19)

Heat flux $E_r = Q\tau_a F_P$ Eq. (20)

SOLID PLUME

Surface emitted power
For conventional solid plume
$SEP = (m_B A\Delta H_C/A_f)F_S$ Eq. (21)
For Modified solid plume
$SEP = (1 - \varsigma)SEP_{max} - \varsigma SEP_{soot}$ Eq. (22)
$SEP_{max} = (m_B A\Delta H_C/A_f)F_S$ Eq. (23)

Atmospheric transmmissivity
$\tau_a = 2.02(P_w X_s)^{-0.09}$ Eq. (24)

Heat flux $E_r = SEP\ \tau_a F_{21}$ Eq. (25)

Figure 3. Point source models steps and equations

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Case study

A terminal consists of a medium, and fourteen large floating roof crude oil storage tanks. The capacity of the medium tank is half million barrels, and the capacity of each large tank is one million barrels. The terminal has been constructed since mid-1960s. The large crude oil storage tanks were made up of carbon steel material with dimensions of 100m diameter and 21m height. Each storage tank was provided with secondary circular dike containment. The terminal layout plan is shown in Figure 4.

Figure 4. Crude oil terminal

The crude oil terminal shows that some storage tanks are congested. For convenience, the tanks are numbered A, B, C, D, etc. The storage tanks congested area is bordered with yellow line. The tank shell to shell separation distances are summarized in Table 2. The sea side is the north direction of the terminal. The prevailing wind direction is North West. Storage tanks B, C and storage tanks D, E are located downwind of storage tank E and G respectively.

Table 2. Tank to tank shell separation distance.

Tanks	**Tank to tank shell separation distance (m)**
(E to B) and (E to C) and (G to D)	**50 m**
E to D and E to F	**75 m**
G to E and G to F	**100 m**

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Results and discussion

In order to estimate the thermal radiation from pool fire incident in storage tank two fire scenarios are considered for the calculation(i) S1- fire in the storage tank – whole area (in the event of the floating tank roof sinking) (ii) S2 - Fire in the tank and bund (sunken roof of the storage tank and damaged wall of the storage tank). The input parameters for the calculations are summarized in Table 3.

Table 3. Input parameters.

Input parameters	Value and unites
Crude oil volume (m^3)	160000
Density (kgm^{-1})	855
Heat of combustion ($J\,kg^{-1}$)	42500
Ambient air density ($kg\,m^{-3}$)	1.18
Ambient temperature (C)	25
Gravitational acceleration (ms^{-2})	9.81
Relative humidity	50%
Wind speed (m/s)	0 and 5

To estimate the heat flux at a distance, point source model and solid plume conventional and modified radiation models were used. Burning rate, maximum pool diameter and flame length are parameters which are not affected by the choice of the radiation model. The mass burning rate for hydrocarbon liquids can be estimated by Eq. (8). The area of the pool fire for S1 was calculated using the tank diameter. The area of the pool fire for S2 was calculated using the tank diameter and the bund. The Thomas correlation for still air conditions (Eq. 3, Table 1) was adopted to estimate the pool fire flame length. The geometry of the pool fire in still air conditions with the dimensions are depicted in Figure 5. The flame length was found to be 52m for S1 and 60m for S2.

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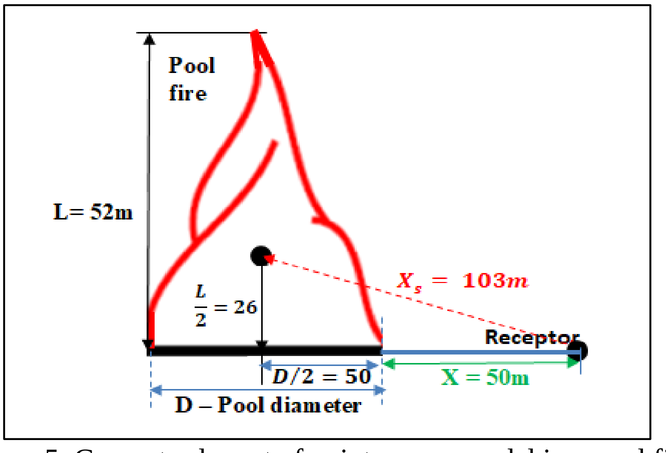

Figure 5. Geometry layout of point source model in a pool fire

The Thomas, Moorhouse and Binding-Pritchard correlations in Table 1 for windy air conditions were used to estimate the pool fire flame lengths. The flame length was summarized in Table 4.

Table 4. Output parameters

Output parameters			
Scenario		**S1**	**S2**
Burning rate, m_B ($kgm^{-2}sec^{-1}$)		**0.02833**	**0.02833**
Diameter, D (m)		**100**	**120**
Area of the pool, A (m^2)		**7850**	**11304**
Flame length, L (m)	**Thomas, 1963 (no wind)**	**52**	**60**
	Heskestad (no wind)	**43**	**46**
	Thomas, 1963 (wind)	**50**	**56.5**
	Moorhouse, 1982(wind)	**97**	**114.2**
	Binding-Pritchard, 1992(wind)	**116.5**	**136**
Distance from the edge of the dike, X(m)		**50**	**50**

In case of a point source model, the distance of the point source to the receptor was calculated using the Pythagoras theorem eq. (16). The distance to the receptor $x_S$was found 103m for S1 and 114m for S2 see Table 6. The energy radiated by the point source was estimated by using eq. (17), Q was found 9451.6 MJ S^{-1} for S1 and

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13610.3MJ S^{-1} for S2. The distance $x_S$was used in eq. (18) for the calculation of the atmospheric transmissivity, and in eq. (19) for the determination of the geometric view factor. The heat flux $E_r$at distance was determined using eq. (20). $E_r$was found to be 48 kWm^{-2} for S1 and 56 kWm^{-2} for S2. Table 5 summarizes point source model results

Table 5. Point source model results

Point source model		
Scenario	**S1**	**S2**
Distance from the point source to the receptor, x_S (m)	**103**	**114**
Energy radiated by the source, Q (MJ S^{-1})	**9451.6**	**13610.3**
Atmospheric transmissivity, τ_a	**0.676**	**0.670**
Geometric view factor, F_P (m^{-2})	7.5×10^{-6}	6.13×10^{-6}
Heat flux at Distance, E_r (kWm^{-2})	**48**	**56**

The solid plume radiation model (conventional) no soot assumes that heat is radiated from the visible surface of a flame described as a cylinder for scenario S1 and S2. The diameter of the storage tank is 100m and the diameter of the tank with bund is 120m. The Distance from the surface of the flame to the receptor $X_S$is 50m for S1 and S2. The surface emitted power $SEP$was determined using eq. (21). The SEP was found 203 for S1 and 211 for S2. The distances X_S for S1 and S2 were used in eq. (24) for atmospheric transmissivity calculation and for the calculation of the view factors for untilted flames. Heat flux at distance, Er was found 24.8kWm^{-2} for S1 and 25.3kWm^{-2} for S2. Figure 6 and Figure 7 show the dimensions of the pool fire solid plum conventional and modified for S1.

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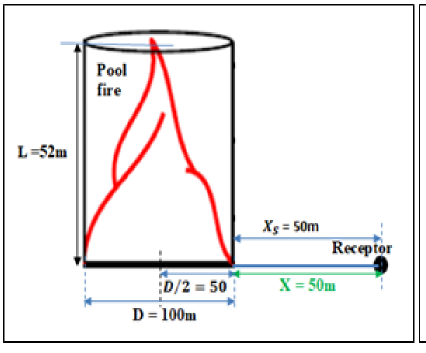

Figure 6. Pool fire solid plume (conventional)

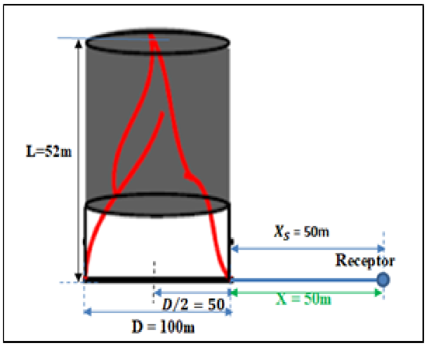

Figure 7. Pool fire solid plume modified

The solid plume radiation model (modified) assumes the flame is covered with soot. In case of pool fire, a large amount of soot is generated, which cover the visible flame and absorbs much of the radiation emitted. The fraction of the pool fire flame surface covered by soot is 0.8 and the emissive power of smoke, SEPsoot, is approximately 205.5kWm^{-2}. Thus, the surface emissive power, SEP, is a combination of the maximum surface emissive power of "pure" flame, SEPmax, and the emissive power of smoke, SEPsoot. Hence, eq. (22) was used to calculate the surface emissive power. The heat flux Er for the solid plume radiation model (modified) was calculated using eq. (25).The Er was found 5.5 kWm^{-2} and 7 kWm^{-2}. Table 6 summarizes Conventional and modified solid plume model results.

Table 6. Conventional and modified solid plume model results

Solid Plume Model	**Conventional (no soot)**		**Modified (flame covered with soot)**	
Scenario	**S1**	**S2**	**S1**	**S2**
Diameter, D (m)	**100**	**120**	**100**	**120**
flame surface area, A_f (m^2)	**16328**	**22608**	**16328**	**22608**
Distance from the flame surface to the receptor, x (m)	**50**	**50**	**50**	**50**

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Surface Emitted Power, SEP ($Js^{-1}m^{-2}$)	**203**	**211**	**45**	**9.4**
Atmospheric transmissivity	**0.678**	**0.667**	**0.678**	**0.667**
Geometric view factor, F_{21}	**0.18**	**0.18**	**0.18**	**0.18**
Heat flux at Distance, *Er* (**kWm^{-2}**)	**24.8**	**25.3**	**5.5**	**7**

The thermal radiations which are resulted in from point source model were found 48kWm^{-2} from the flame in the tank (scenario S1) and 56kWm^{-2} from the flame of tank and bund (scenario S2). The thermal radiations are very high; they exceed the permissible targeted criteria level 31.1 KW for structure at distance 50m from the tank. The thermal radiation which is resulted in from solid plume (conventional) was found 24.8kWm^{-2} for S1 and 25.3kWm^{-2} for S2. Although the thermal radiation level at 50m from the surface of the flame is below the permissible targeted criteria level 31.1 KW for structure, however the operators and emergency responders are at high risk of thermal radiation. The thermal radiation which is resulted in from solid plume (modified) was found 5.5 kWm^{-2} for S1 and 7 kWm^{-2} for S2. The solid plume model (modified) takes into account the effect of the smoke. The smoke reduces the thermal radiation level up to 80%. The thermal radiation below the targeted criteria for structures but it is considered high for operators and emergency responders.

Conclusion

The thermal radiation hazards associated with hydrocarbon storage tank is very high dangerous due to leakage of fuels resulting in huge loss of property and life.

The thermal radiation hazards from pool fire in storage tank have been evaluated by point source and solid plume models for two fire scenarios; fire in the storage tank and fire in the tank with bund.

The thermal radiations which have been estimated by point source model in both scenarios were found to be exceeding the permissible targeted criteria level for structure. Although the thermal radiation from solid plume was found to be below the permissible targeted

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criteria level for structure, however the operators and emergency responders are at high risk of thermal radiation.

Tank farms layout considering the safe separation distance between storage tanks, and adhering to standard codes for implementing of basic process control system, prevention system (safety instrumented system) and mitigation system (firefighting system and emergency response planning) can safeguard the storage tanks from incidents, and minimize the impacts of the thermal radiation consequences in case of fire incidents.

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