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Analysis of Fire and Explosion Consequences in Accidents Involving Premium Gasoline Tanker Trucks

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Abstract

A series of accidents frequently occur in the fuel transport process in Indonesia, resulting in explosive incidents. This study explores the implications of fires and explosions in Premium Fuel tanker truck accidents in Bintaro Permai, focusing on identifying hazard zones and the extent of possible damage. The aim is to map the hazard zones and assess the potential level of damage due to fire and explosion of Premium fuel tanker trucks in the area. Quantitative methods were used with pool fire modelling and the TNT (Trinitrotoluene) method. This study showed that the pool fire modelling found the highest heat flux value in the pool with a pool diameter of 20 m and a distance to the receptor of 11 m, with a value of 14.85 kW/m2. Meanwhile, in modelling the explosion using the TNT Method, an overpressure value of 175.75 kPa was found for a volume of 20,000 L and a distance of 50 m.

Keywords:
Heat Flux, Overpressure, Pool Fire, TNT Method

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INTRODUCTION

Fuel transportation in Indonesia has become an important milestone in supporting economic activity and mobility [1]. However, accidents that often lead to fires and explosions of fuel tanker trucks (BBM) have become issues that affect various aspects, ranging from environmental damage and threats to public safety to adverse economic impacts [2]. Investigations into similar accidents from 2011 to 2019 have been conducted by the Ministry of Energy and Mineral Resources, in which 30 fuel transport accidents were recorded [3]—one in Bintaro Permai in 2013. There was an accident when a truck passed through a railway track and was hit by an electric rail train (KRL), resulting in a fire and explosion from a tanker truck. The fire and explosion of the fuel tanker truck resulted in severe casualties and damage [4].

The analysis of consequences related to truck tanks involves the development of fire and explosion models utilizing pool fire simulations and TNT methods. Pool fires are among the most common fire incidents in the context of chemical storage in tanks. Within a tank storage facility, large-scale tank fires exhibit two primary characteristics. First, extinguishing large tank fires can be challenging, and the associated material losses can be significant. Second, these types of fires can trigger a domino effect due to thermal radiation [5]. Radiation typically contributes approximately 92-100% of tank fire heat load, while convection plays a minor role at around 0-8%.

Similarly, radiation accounts for approximately 100% of the heat load in open pool fires, with no convection present [5]. Consequently, radiative heat flux represents the primary factor in escalating the severity of pool and open tank fires. The application of deterministic mathematical models to describe thermal radiation from pool fires has been employed in previous research. It is pivotal in assessing damage and potential consequences for individuals [6]. This model is one of the engineering methods that fall under manual calculations used to evaluate the impact of pool fires and is currently actively applied [7]. Pool fire simulation methods have evolved rapidly from manual calculations to CFD simulations, and many studies have been published in recent years [8]. However, a CFD simulation application does not seem to be specifically used to tackle pool fires associated with road or railway accidents.

When a pool fire occurs, the fire will boil the tank, making the liquid hydrocarbon material partially gaseous so that the next stage will be an explosion. The impact of a confined explosion can be severe, it can damage the structural elements of the building and even threaten the safety of humans in the vicinity. In previous studies, researchers still used the TNT method to identify the consequences of exploding hydrocarbon explosions [9]. When evaluating the effects of explosions across a variety of target structures, issues emerge when alternative high-explosive materials are employed instead of Trinitrotoluene (TNT). Empirical formulations, such as those proposed by Kingery and Bulmash, are one such example [10]. TNT uses the concept of equivalence to identify shock waves in the context of explosives.

Nevertheless, three drawbacks are associated with applying the equivalence concept to TNT usage. Firstly, no definitive data or a consistent methodology can offer precise and reliable TNT equivalence values. Additionally, TNT equivalence factors may vary depending on the level of overpressure. Thirdly, the TNT equivalence factor can change with variations in scaled distance [11].

This paper discusses what kind of consequences will be received by the community and other structures when an accident occurs in the Bintaro Permai area. The hydrocarbon spill triggered the pool fire and produced energy released from the explosion. In such explosions, the TNT method is performed by measuring the energy or explosive power produced by a particular material, then comparing it with the equivalent TNT explosion in terms of detonation energy [12].

Pool Fire

A pool fire is a fire resulting from liquid fuel ignition, for example, fuel oil or flammable chemicals, spilling and forming a burning pile on the ground or other surface. This phenomenon can be elucidated by performing a heat flux calculation for a pool fire, which involves a series of significant steps. Figure 1 is used to illustrate the stages of the calculation [13].

1. Burning Rate

Equation (1) shows the formula for burning rate m' in kg/m^{2}s, where ΔH_C is heat of combustion (J/kg), ΔH_V is the heat of evaporation (J/kg), ρ_L is the density of liquid fuel at its boiling temperature (kg/m^3), C_p refers to the fuel's spevific heat capacity (J/kgK), T_b and T_a corresponds to the fuel's boiling point and the surrounding environmental temperature. (K), C_1 1,27 x 10^{-6} (m/s).

$$m' = \rho_L C_1 \frac{\Delta H_C}{\Delta H_V + C_P(T_b - T_a)} \quad (1)$$

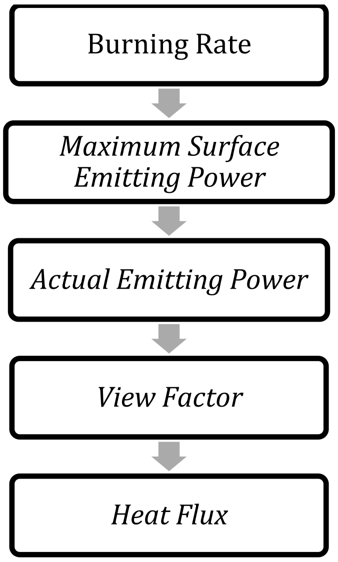

Figure 1. Pool Fire Stages

2. Maximum Surface Emitting Power

Equation (2), (3) and (4) shows how to calculate the maximum surface emitting power. Where SEP_{max} represents the maximum surface emitting power (kW/m^2), F_S represents radiation fraction, m' represents burning rate (kg/m^{2}s) the value of F_S for each substance shows in Table 1, L represents the average flame length (m), D represents pool diameter (m), ΔH_C represents Heat of combustion (J/kg), ρ_{air} represent air density (kg/m^3), g represent gravity (m/s^2), u^* represent dimensionless wind velocity if $u^*<1$ then $u^*=1$ and u_w represent wind velocity (m/s).

$$SEP_{max} = F_s \frac{1}{1+4\left(\frac{L}{D}\right)} m' \Delta H_c \quad (2)$$

$$\frac{L}{D} = 10.615 \left[\frac{m\prime}{\rho_{air}\sqrt{gD}}\right]^{0.305} (u^*)^{-0.03} \quad (3)$$

$$u^* = u_w \left(\frac{gm\prime D}{\rho_{air}}\right)^{-1/3} \quad (4)$$

Table 1. Radiation Fraction

Substance	D (m)	F_S (-)
Methanol	0.076	0.162
	0.152	0.165
	1.220	0.177
Methane	0.305	0.210
	0.760	0.230
	1.530	0.15-0.24
	3.050	0.24-0.34
	6.100	0.20-027

Substance	D (m)	F_S (-)
Gasoline	1.22	0.30-0.40
	1.53	0.16-0.27
	3.05	0.13-0.14
Benzene	0.076	0.350
	0.457	0.345
	0.760	0.350
	1.220	0.360
Butane	0.305	0.199
	0.457	0.205
	0.700	0.269

3. Actual Emitting Power

Equation (5) shows the formula to calculate actual emitting power. Where D constitutes for the pool fire's diameter.

$$SEP_{act} = 140e^{-0.12D} + 20(1 - e^{-0.12D}) \tag{5}$$

4. View Factor

F_{view} (-) is the fraction of radiation reaching receptors within a given area (receptors can be individuals or objects). The shape of the fire has the shape of a cylindrical shaft that tends to tilt. The angle of inclination, denoted as θ, characterizes the cylinder's tilt resulting from wind effects. Equation (6) shows the view factor F_{view}, It is derived from its perpendicular contribution Fv Eq. (7) and the horizontal contribution Fh Eq. (7).

$$F_{view} = \sqrt{F_V^2 + F_h^2} \tag{6}$$

$$\pi F_v = -E\, tan^{-1} D + E\left[\frac{\alpha^2+(\beta+1)^2-2\beta(1+\alpha\sin\theta)}{AB}\right] tan^{-1}\left(\frac{AD}{B}\right) + \frac{cos\theta}{C}\left[tan^{-1}\left(\frac{\alpha\beta-F^2\sin\theta}{FC}\right) + tan^{-1}\left(\frac{F\sin\theta}{C}\right)\right] \tag{7}$$

$$\pi F_h = tan^{-1}\left(\frac{1}{D}\right) + \frac{\sin\theta}{C}\left[tan^{-1}\left(\frac{\alpha\beta-F^2\sin\theta}{FC}\right) + tan^{-1}\left(\frac{F\sin\theta}{C}\right)\right] - \left[\frac{\alpha^2+(\beta+1)^2-2(\beta+1+\alpha\beta\sin\theta}{AB}\right] tan^{-1}\left(\frac{AD}{B}\right) \tag{8}$$

5. Heat Flux

Where P_w represents the partial vapor pressure within the atmosphere, P_W^o represents vapor pressure saturation (Pa), RH is the humidity ratio, and C4 $2.02P_a^{0,09}m^{0,09}$.

$$q' = SEP_{act}F_{view}\tau_a \tag{9}$$

$$\tau_a = C_4[P_w(X - R)]^{-0,09} \tag{10}$$

$$P_w = RHP_W^o \tag{11}$$

TNT Method

TNT is based on the principle that the explosive power of a vapor cloud is equivalent to the mass of TNT capable of generating a similar explosive force. In the context of tank explosion, this concept leads to calculating thermal impact and pressure due to explosion. Overall, utilizing the TNT Method as a preliminary estimate in determining blast impact has general advantages in blast analysis. However, the TNT method has drawbacks, such as overestimating pressure without considering the configuration of the room where the explosion occurs, uncertainty in the energy fraction parameter, which is often unknown in many cases, significantly affecting the prediction, and the inability to calculate the time progression of the explosion [14]. Figure 2 performs calculation steps that can be expressed through mathematical equations [13].

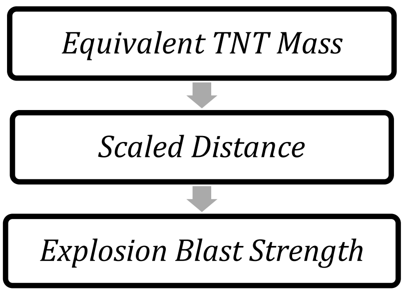

Figure 2. TNT Method Stages

1. Equivalent TNT Mass

Where M_G (kg) indicates the quantity of combustible gases participating in the explosion (kg), ΔH_C is heat combustion, ΔH_{TNT} (4.760 (kj/kg), f_E ignifies the proportion of energy discharged as shock waves (0.01 and 0.1).

$$M_{TNT} = \frac{f_E \, \Delta H_C \, M_G}{\Delta H_C} \quad (12)$$

2. Scaled Distance

When X denotes the distance from the epicenter of the explosion.

$$Z = \frac{x}{M_{TNT}^{1/3}} \quad (13)$$

3. Explosion Blast Strength

Where P_S is a overpressure (kPa) and Z is a distance scale (m/kg$^{1/3}$)

$$P_s = \frac{\left[88{,}800\left(1+\left[\frac{Z}{4.5}\right]\right)\right]}{\sqrt{1+\left[\frac{Z}{0.048}\right]^2}\sqrt{1+\left[\frac{Z}{0.32}\right]^2}\sqrt{1+\left[\frac{Z}{1.35}\right]^2}} \quad (14)$$

METHODOLOGIES

The application used in this study, as a step-by-step process carried out in Figure 3, starts by reading the news of the accident and taking data verified through the National Transportation Safety Committee [4]. Consequence modeling is used as it happened that day, with a fire and explosion. To calculate the heat flux from the pool fire and the overpressure resulting from the explosion, supporting data such as atmospheric data, fuel content, diameter of the fire pool, fuel mass, and tank volume are needed. After obtaining the results of heat flux and excess pressure, the danger zone and damage level can be determined which is translated through IOGP (International Association of Oil and Gas Producers) data to determine the level to be experienced at a specific radius [15].

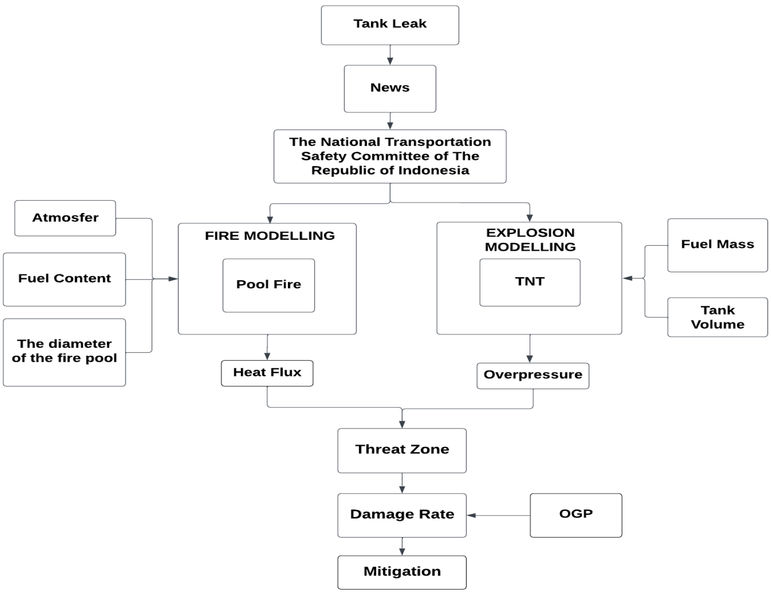

Figure 3. Conceptual Model

RESULT AND DISCUSSION

Modelling the consequences of a fuel tank fire and explosion focuses on the value of the flame heat flux and the overpressure of the explosion. In this case, variations are made, ranging from the distance of the pool's diameter, the distance of the receptors, and the volume of the explosion. Following the simulation of the impacts arising from a fire and explosion in a fuel tank, it is essential to explore measures for alleviation to minimize potential hazards.

Result

In this section, we present the findings supported by the data obtained. Table 2 categorizes the hazard zone levels related to thermal radiation, essential in identifying and mapping the hazard zones in a tank fire event [16].

Table 2. Level of Concern Thermal Radiation

Zone	Heat Flux	Consequences
Red	≥ 10 kW/m^2	Potential death within 60 seconds
Orange	5 - 9 kW/m^{2}kW/m^2	Potential 2nd degree burns within 60 seconds
Yellow	2 - 4 kW/m^{2}kW/m^2	Potential pain within 60 seconds

Table 3 is used to categorize the level of concern against overpressure. In the context of tank explosions, Table 3 is used to evaluate and classify hazard zones that may arise due to overpressure [17].

Table 3. Level of Concern Overpressure

Zone	Overpressure	Consequences
Red	$\geq$ 55.15 kPa	Can destroy buildings
Orange	24.13 kPa – 54 kPa	May allow serious injury
Yellow	6.89 kPa – 23 kPa	Can Shatter Glass

Table 4 is used to detail the heat flux calculations resulting from the pool fire, as well as to inform a deeper understanding of the thermal impacts that can arise in such situations. Table 5 details the calculations associated with overpressure arising from tank explosions, and this information supports further analysis of potential risks.

Table 4. Heatflux Calculation

Pool Diameter (m)	Heat Flux (kW/m^2)					
	X=11 (m)	X=22 (m)	X=33 (m)	X=44 (m)	X=55 (m)	X=66 (m)
5	5,84	3,36	2,48	1,97	1,63	1,39
10	8,66	3,80	2,40	1,77	1,41	1,18
15	11,16	4,52	2,67	1,81	1,34	1,05
20	14,85	5,21	3,05	2,04	1,46	1,10

Table 5. Overpressure Calculation

Volume (L)	Overpressure (Ps(kPa))						
	X= 50 (m)	X= 100 (m)	X= 150 (m)	X= 250 (m)	X= 350 (m)	X= 450 (m)	X=550 (m)
20.000	113,01	27,07	14,00	7,12	4,83	3,67	2,97
15.000	62,21	17,19	9,62	5,20	3,60	2,67	2,24
10.000	25,25	8,94	5,49	3,15	2,22	1,72	1,40
5.000	113,01	27,07	14,00	7,12	4,83	3,67	2,97

Figure 4 shows the correlation between several parameters and heat flux that occurs in a pool fire. This helps identify factors that influence thermal impact.

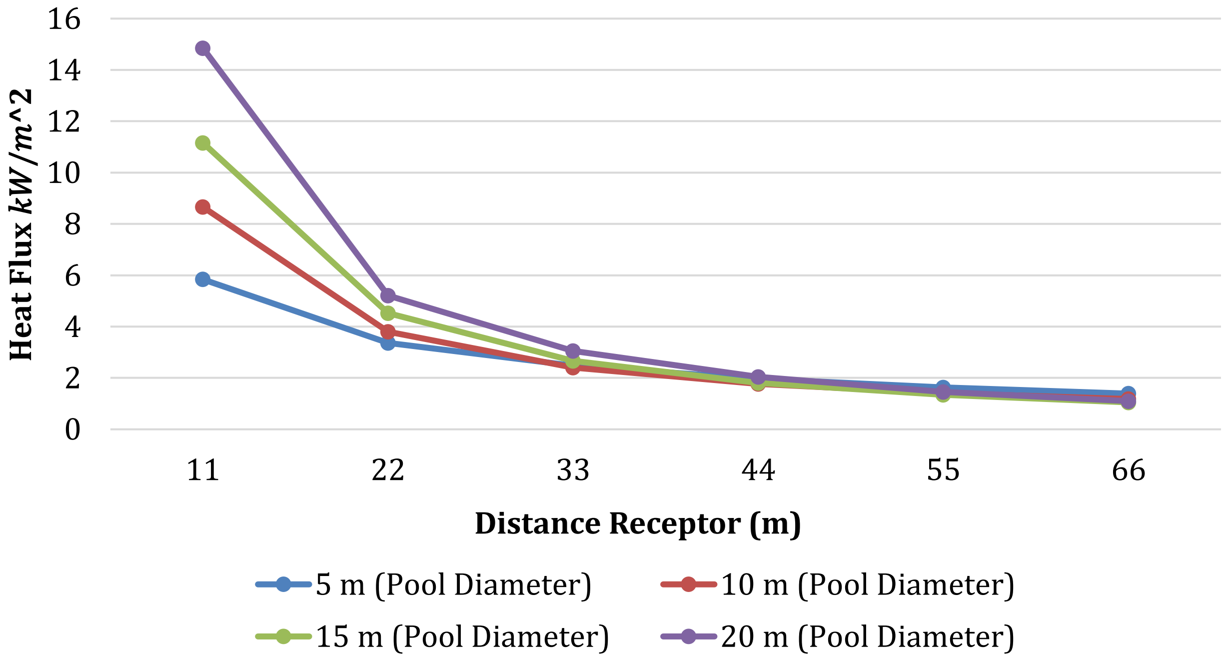

Figure 4. The relationship of several parameters with heatflux

Figure 5 illustrates the correlation between several parameters and the overpressure that occurs in the tank explosion. It provides insight into the variables that contribute to the overpressure. Hazardous area delineation will be employed to ascertain the extent of both safe and unsafe zones adjacent to the railroad tracks.

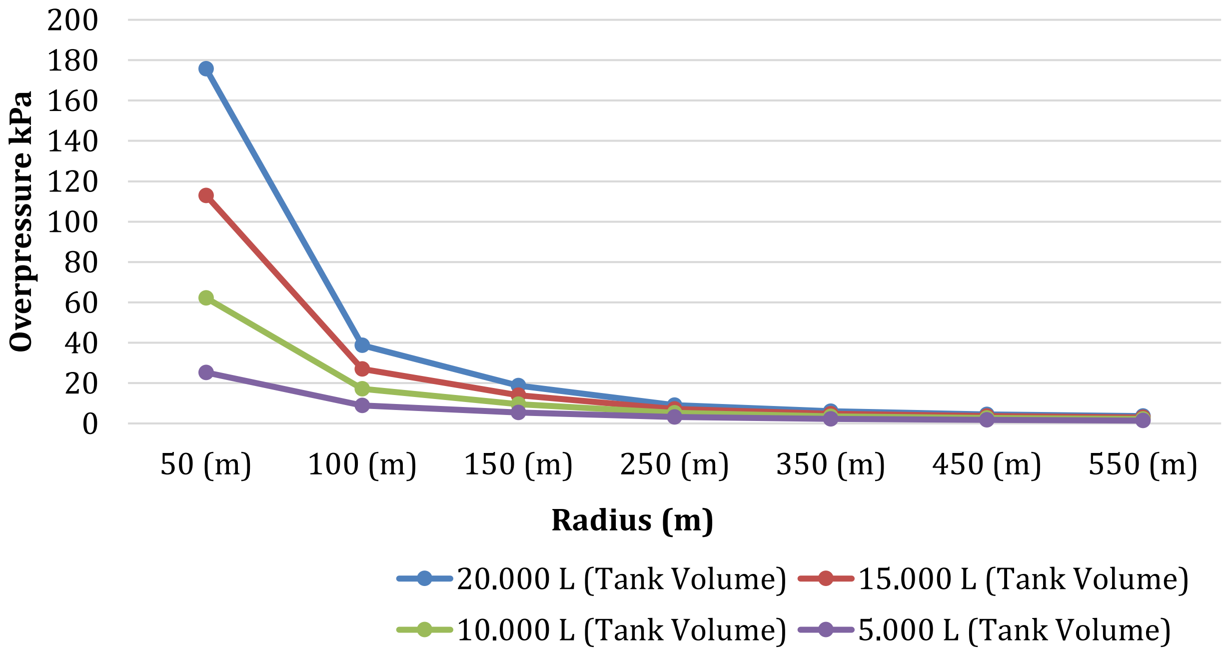

Figure 5. The relationship of several parameters with Overpressure

Figure 6 depicts a visualization of the threat zones that may arise from pool fire, at certain distances (5 m, 10 m, 15 m, and 20 m). Figure 7 shows the threat zone that can result from overpressure in a tank explosion, with variations in tank capacity when it explodes (5,000 L, 10,000 L, 15,000 L, and 20,000 L).

Mitigation initiatives involve disseminating knowledge about the potential dangers of fuel tanker truck leaks and offering specialized training in fire prevention strategies for drivers, security personnel, and nearby communities. Additionally, collaborative efforts aim to promote awareness and fundamental skills related to Hazardous Chemical Road Transportation Awareness (HCRTA) for accident prevention and community evacuation [18].

Figure 6. Threat Zone Pool Fire (5 m, 10 m, 15 m, 20 m)

Figure 7. Threat zone overpressure (5,000 L, 10,000 L, 15,000 L, 20,000 L)

Discussion

Based on the calculation of heat flux performed, Figure 4 shows that the diameter and radius of the pool fire strongly influence the heat flux in pool fire. Modelling the diameter and radius of the fire estimates higher heat flux to the receptor, especially for a radius closer to the edge of the flame pool diameter [19]. The accelerated decrease in heatflux that occurs in ponds with a diameter of 20 m compared to 5 m with the same receptor distance of 66 meters is caused by the spill factor of the hydrocarbon material itself. A swimming pool fire with a diameter of 5 m will have a surface area smaller than a diameter of 20 m. As a result, the heat emitted by a pool fire with a diameter of 5 m will be more concentrated in a smaller area, producing a higher heat flux at a distance of 66 meters.

Based on the overpressure calculations performed, Figure 5 explains that the overpressure is affected by volume and distance. The volume of hydrocarbon material deposited is required to estimate the overpressure resulting from an explosion, while the extent of damage is affected by distance [20].

Table 2 shows the threat zones caused by the pool fires, which explains that the red zone due to heat flux is at a value > 10 kW/m^2 with the potential for death within 60 seconds. With differentiated data by KNKT, the fire occurred 13 m from the fire spot. This proves the calculation of pool fires carried out, which refer to Table 4. Especially on ponds with a diameter of 15 m. Where at a receptor distance of 11 m heat flux was obtained at 11.16 kW/m2 including the red zone, a receptor distance of 22 m was obtained at 4.52 including the orange zone and a receptor distance of 33 m was obtained at 2.67 kW/m^2 including the kW/m^2 yellow zone.

Table 3 is the overpressure threat zone category, which explains that the red zone, due to overpressure is at a value of > 55.15 kPa, which can destroy buildings. Data obtained from KNKT shows that some buildings were destroyed, but they only occurred at a distance not far from the explosion point. Table 5 proves the overpressure calculations, especially at an explosive volume of 5,000 L. At a distance of 50 m, overpressure is obtained at 25.25 kPa, including the orange zone. In the yellow zone, it reaches a distance of 250 m, and excess pressure is obtained at 8.93 kPa to 3.15 kPa. In the red zone, it is ensured to occur below a distance of 50 m.

CONCLUSIONS AND RECOMENDATION

Conclusions

The diameter of the fire pool, the radius, and the volume of the explosion influence the consequences of fires and explosions. The extremely hazardous zone is found from a pool fire with a diameter of 20 m, and the distance of a receptor is within 11 m. Meanwhile, a dangerous zone of overpressure occurs with a receptor distance of less than 50 m. By considering these factors, we can take appropriate prevention and mitigation measures such as providing public awareness, safety training, and collaborating with relevant agencies to protect the environment, people, and assets. To protect the environment, people and assets involved in explosion and fire scenarios. Safety should remain the top priority in planning and dealing with the possible impacts of these phenomena.

Recomendation

From the results of the research that has been done, researchers can provide some suggestions that are believed to make a significant contribution to future research. These suggestions summarize the various potential improvements that can be explored in future research. For example, taking efforts to utilize weather or atmospheric data that includes extreme conditions, such as significantly low or high temperatures, will provide a deeper perspective. This step can reveal the potential impact of fires and explosions on fuel tanks in unusual environmental situations, enriching our understanding of the complexity and variety of risks that may be involved. In addition, further exploration of various types of hydrocarbon materials can open new insights regarding the risk of fires such as ball fire, jet fire and flash fire, while the application of different models in explosion analysis, such as the Multi Energy Method and Baker-Strehlow Method, can be considered a progressive step that deepens understanding of the complexity of the phenomenon. Therefore, these recommendations provide valuable guidance in directing future research toward higher levels of excellence.

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