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Hydraulic-Based Evaluation of Fire Water System Adequacy for Dike-on-Fire Scenario at Gasoline Storage Tank

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Abstract

Dike-on-fire incidents in hydrocarbon storage tank facilities have significant escalation potential due to prolonged thermal radiation exposure and adjacent tank involvement. This study evaluated the adequacy of the existing fire water system under a gasoline storage tank dike-on-fire scenario at PT X Refinery using PHAST consequence analysis, firefighting demand calculation, and PIPENET hydraulic simulation. Fire consequence analysis was conducted to evaluate thermal radiation exposure, while firefighting demand and hydraulic analyses were performed based on NFPA and API standards. The simulation results showed that thermal radiation intensity of 12.5 kW/m² extended up to approximately 83 m from the fire source, indicating escalation potential within the tank farm area. The required fire water demand reached 11,665.68 gpm, while the available hydraulic firefighting capacity reached 13,017.50 gpm under simultaneous cooling and firefighting operations. However, operational limitations of the existing HCFM capacity resulted in a prolonged minimum firefighting discharge duration of 83.12 min. The results indicate that the existing fire water system was hydraulically capable of supporting emergency response operations for the analyzed dike-on-fire scenario.

Keywords: dike-on-fire; fire water system; hydraulic analysis; PHAST; storage tank fire

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INTRODUCTION

The oil and gas industry is one of the industrial sectors with a high risk of fire incidents due to the characteristics of its processes and the use of large quantities of flammable hydrocarbon materials (Pramesti et al., 2024). Hydrocarbon storage tanks are considered critical facilities in refinery operations because they contain volatile and combustible substances that may lead to fire and explosion incidents with consequences including casualties, asset damage, operational disruption, and environmental impact (Sotoodeh, 2023). In addition, fires involving storage tanks may escalate into domino effect scenarios due to thermal radiation exposure and fire propagation to adjacent tanks and process units (Baser & Behnam, 2020). Therefore, hydrocarbon storage tanks are categorized as high-risk facilities requiring reliable fire protection systems and emergency response strategies.

According to the Directorate General of Oil and Gas of the Ministry of Energy and Mineral Resources of Indonesia (2022), hydrocarbon storage tank fires have occurred in several refinery facilities in Indonesia, indicating that tank fires remain significant industrial hazards despite the implementation of existing fire protection systems. At PT X Refinery, one of the critical assets is a gasoline storage tank with an approximate storage capacity of 157,000 barrels. Large gasoline inventories may produce prolonged burning duration, high heat release rates, and significant fire escalation potential during fire incidents. Kwon et al. (2021) reported that gasoline tank fires are difficult to extinguish and may require substantial firefighting resources due to the intensity and duration of the fire. These conditions indicate the importance of evaluating fire protection systems and firefighting capability for gasoline storage facilities.

Sotoodeh (2023) explained that active fire protection systems such as fire water systems, hydrants, and foam systems are designed to support extinguishing operations, while passive fire protection systems function to limit fire propagation. However, the availability of fire protection systems does not necessarily guarantee firefighting effectiveness under specific fire scenarios, particularly in large-scale hydrocarbon fires. Fire protection systems in storage tank facilities therefore require quantitative evaluation to determine whether the existing system capability is sufficient to support firefighting operations during emergency conditions. In addition, NFPA 1620 states that pre-incident planning should include information related to facility characteristics, hazards, firefighting resources, and emergency response strategies (Curless, 2019).

At PT X Refinery, fire protection systems consisting of hydrants, monitors, foam systems, and fire water distribution networks have been installed in tank farm facilities. However, the existing systems have not been quantitatively evaluated under specific fire escalation scenarios, particularly dike-on-fire scenarios in gasoline storage tank areas. In this study, adequacy evaluation was conducted by comparing firefighting demand obtained from fire modeling with the actual capability of the existing fire protection system, including fire water demand, pump capacity, distribution pressure, firefighting equipment requirements, and firefighting duration under emergency conditions.Dunn et al. (2017) stated that the absence of quantitative evaluation may create uncertainty in determining firefighting resource requirements and emergency response effectiveness in hydrocarbon storage facilities.

Previous studies have discussed tank fire behavior, thermal radiation, and domino effect escalation in hydrocarbon storage facilities. Khodabakhsh et al. (2026) evaluated tank vulnerability and domino effect propagation, but did not integrate fire modeling and hydraulic analysis in evaluating fire protection system adequacy. Nam et al. (2026) studied firefighting techniques for gasoline tank fires; however, the study mainly focused on empirical firefighting approaches without quantitative evaluation of fire protection system capability.

In addition, PHAST simulation studies showed that domino effects may occur rapidly if fire escalation is not immediately controlled (Baser & Behnam, 2020). Chen et al. (2025) also reported that pool fire scenarios have significant escalation potential in densely arranged storage tank facilities. Nevertheless, limited studies specifically evaluate the adequacy of fire water systems using hydraulic analysis under dike-on-fire scenarios in gasoline storage tank facilities.

Hydraulic analysis is required to evaluate whether the existing fire water system is capable of supplying sufficient firefighting flowrate and maintaining operational hydraulic performance during simultaneous firefighting operations. Parameters such as fire water demand, fire pump capacity, pressure distribution, and hydrant performance become important factors in determining firefighting capability during large-scale tank fire scenarios. Therefore, a hydraulic-based evaluation is necessary to quantitatively compare firefighting demand with the actual capability of the existing fire protection system under a dike-on-fire scenario.

This study aims to evaluate the adequacy of an existing fire water system under a dike-on-fire scenario at a gasoline storage tank using a hydraulic-based approach. The evaluation was conducted through fire scenario analysis, firefighting demand calculation, and hydraulic analysis of the existing fire water network to determine whether the available fire protection system is capable of supplying sufficient firefighting flowrate and maintaining operational hydraulic performance during simultaneous firefighting operations.

MATERIALS AND METHODS

This study applied an engineering-based evaluation approach to assess the adequacy of an existing fire water system under a dike-on-fire scenario at a gasoline storage tank facility. The study consisted of fire consequence analysis using PHAST 9.0, firefighting demand calculation based on NFPA and API standards, and hydraulic simulation of the existing fire water network using PIPENET software.

Study Object and Fire Scenario

This study was conducted at a gasoline storage tank facility located at PT X Refinery. The evaluated tank was an external floating roof storage tank containing gasoline product with an approximate storage capacity of 157,000 barrels. The tank farm area was equipped with hydrants, monitors, foam systems, fire water distribution pipelines, and fire pumps. The analyzed fire scenario was a dike-on-fire scenario caused by gasoline spill and ignition within the bundwall area surrounding the storage tank. The scenario dimensions and surrounding equipment configuration were determined based on the actual tank farm layout.

Fire Consequence and Firefighting Demand Analysis

Fire consequence analysis was conducted using PHAST 9.0 software to evaluate thermal radiation contours and escalation potential under the analyzed dike-on-fire scenario. The simulation was performed using operating conditions, hydrocarbon inventory, and environmental parameters obtained from the gasoline storage tank system.

Firefighting demand analysis was performed based on NFPA 11, NFPA 15, API RP 2001, and API RP 2030 standards by considering cooling water requirements for adjacent tanks and foam application requirements for dike-on-fire scenarios. The required firefighting capacity consisted of cooling water demand, foam solution demand, and water demand for foam application.

According to NFPA 15 and API RP 2030, adjacent tanks exposed to thermal radiation shall be protected using water spray cooling systems. Cooling water demand for adjacent tanks was calculated based on the exposed shell surface area using Equation (1).

$$Q_c = \pi \times d \times h \times r \times C \qquad (1)$$

where Q_c is cooling water demand (L/min), d is tank diameter (m), h is exposed tank height (m), r is cooling water application rate (L/min/m²), and C is section coverage factor.

The cooling water application rate used in this study was 4.1 L/min/m² based on API RP 2030 recommendations for hydrocarbon storage tank exposure protection under radiant heat conditions (American Petroleum Institute, 2022).

Foam demand for dike fire suppression was calculated based on NFPA 11 requirements for fixed foam application on diked hydrocarbon liquid fires using Equation (2).

$$V_f = A \times R_f \times C_f \times t \qquad (2)$$

where V_f is foam concentrate requirement (L), A is dike surface area (m²), R_f is foam application rate (L/min/m²), C_f is foam concentrate proportion (%), and t is foam discharge duration (min).

The foam application rate used in this study was 6.5 L/min/m² with a minimum discharge duration of 30 min based on NFPA 11 requirements for foam monitor protection of diked hydrocarbon liquid fires (NFPA, 2016).

Hydraulic Analysis of Fire Water System

Hydraulic analysis was conducted to evaluate the capability of the existing fire water system in supplying the required firefighting demand during emergency conditions. The evaluated network consisted of fire pumps, ring main pipelines, hydrants, monitors, and foam systems installed in the tank farm facility.

Steady-state hydraulic simulation was performed using PIPENET software to analyze flowrate distribution, pressure distribution, and hydrant hydraulic performance under the analyzed dike-on-fire scenario. Hydraulic simulation was conducted under simultaneous cooling and firefighting operations using the firefighting demand obtained from the firefighting demand analysis.

Hydraulic performance evaluation included total available firefighting flowrate, hydrant outlet pressure, and fire pump operating condition during firefighting operations. Hydraulic adequacy was evaluated by comparing the required firefighting demand with the available hydraulic capacity of the existing fire water system.

According to API RP 2030, acceptable hydraulic performance shall maintain adequate firefighting flowrate and operational pressure during simultaneous firefighting operations. Therefore, the hydraulic simulation results were used to determine whether the existing fire water system was capable of supporting emergency response operations under the analyzed dike-on-fire scenario.

RESULTS AND DISCUSSION

Fire Scenario and Thermal Radiation Analysis

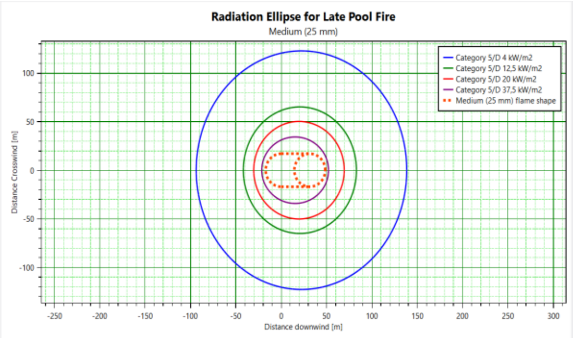
The analyzed fire scenario was a dike-on-fire incident involving gasoline storage tank D-320-07B located in Plant Feed and Product Tankage Unit #320 at PT X Refinery. Based on the incident scenario, an initial rim seal fire caused by lightning strike escalated into a full surface tank fire and subsequently resulted in tank failure. The tank rupture caused gasoline release and accumulation within the bundwall area, leading to a large-scale dike-on-fire scenario affecting adjacent tanks located within the same dike area. This scenario was categorized as a high-risk fire event due to the large gasoline inventory and the potential for fire escalation to nearby equipment.

Fire consequence analysis was conducted using PHAST 9.0 to evaluate thermal radiation exposure generated by the dike-on-fire scenario. The simulation was performed using operating conditions, hydrocarbon inventory, and environmental parameters obtained from the gasoline storage tank system.

Table 1. Fire Scenario and Simulation Parameters

Parameter	Value
Fire scenario	Dike-on-fire
Tank type	External floating roof tank
Stored material	Gasoline
Leak hole diameter	25 mm
Inventory volume	20,905 m³
Operating Temp.	40 °C
Operating pressure	Atmospheric
Flash point	-49 °C
Heat of combustion	3.94E+09 J/kmol
Wind speed	5 m/s
Atmospheric stability	Pasquill D
Ambient temperature	29.6 °C
Pool diameter	34.00 m

The PHAST simulation results demonstrated that the dike-on-fire scenario generated significant thermal radiation exposure surrounding the tank farm area. The resulting radiation contour indicated that adjacent gasoline storage tanks D-320-07A and D-320-07C located within the same bundwall area were exposed to elevated thermal radiation, indicating the potential for fire escalation and domino effects under prolonged pool fire conditions. The thermal radiation contour generated from the simulation is presented in Figure 1.



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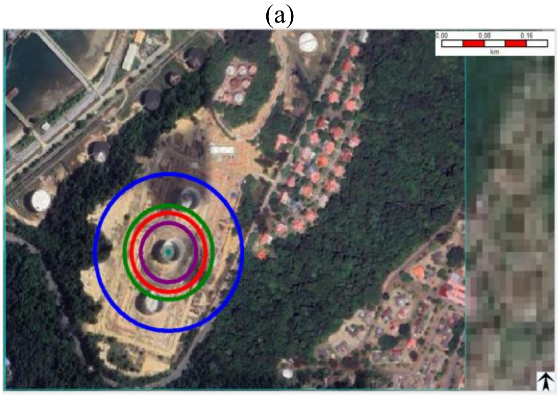

(b)

(c)

Figure 1. PHAST Simulation Result of Thermal Radiation for Dike-on-Fire Scenario

Based on the PHAST simulation results, the estimated safe distance for the analyzed dike-on-fire scenario was greater than 83 m under bund fire conditions. The simulation showed that thermal radiation intensity of 12.5 kW/m² extended up to approximately 83 m from the fire source, while higher radiation intensities of 20 kW/m² and 37.5 kW/m² were concentrated closer to the burning area, as presented in Table 2. These radiation levels indicate substantial exposure risk to nearby equipment and firefighting operations during emergency response activities.

Table 2. Thermal Radiation Level

Radiation Level (kW/m²)	Distance (m)
37.5	52.18
20	69.53
12.5	83.00
5	124.09

The analyzed scenario demonstrated considerable escalation potential within the tank farm area due to prolonged thermal radiation exposure. According to Baser and Behnam (2020), continuous thermal radiation exposure in hydrocarbon storage facilities may accelerate domino effect propagation and increase the probability of adjacent tank involvement. In addition, Kwon et al. (2021) reported that large-scale gasoline tank fires generate high heat release rates and prolonged burning durations, resulting in significant challenges during firefighting operations.

Based on the safety distance criteria published by OGP (2010) thermal radiation exposure of 12.5 kW/m² is categorized as a fire zone with significant fatality potential and severe thermal exposure to nearby equipment and personnel. Meanwhile, radiation intensity of 37.5 kW/m² may result in immediate fatality and ignition of combustible materials under prolonged exposure conditions.

These findings indicate that the analyzed dike-on-fire scenario may expose adjacent tanks and emergency response personnel to hazardous thermal radiation levels. Therefore, adequate cooling systems and sufficient fire water supply are required to prevent further fire escalation within the tank farm area.

The thermal radiation contour indicated that adjacent gasoline storage tanks D-320-07A and D-320-07C located within the same bundwall area were exposed to elevated thermal radiation during the analyzed scenario. Continuous exposure to thermal radiation may increase the probability of fire escalation and adjacent tank involvement under prolonged pool fire conditions.

Firefighting Demand Analysis

The firefighting demand calculation demonstrated a considerable difference between the theoretical firefighting requirement and the existing operational firefighting capacity under the analyzed dike-on-fire scenario. Based on the fire consequence analysis, cooling protection was required for adjacent tanks D-320-07A and D-320-07C located within the affected thermal radiation area. Adjacent tank cooling operations required a theoretical cooling water demand of 331.84 m³/hr for each adjacent tank. However, considering the existing fire water spray configuration, the available cooling flowrate decreased to 223.23 m³/hr per tank.

In addition, the theoretical foam solution demand for offensive firefighting operations was calculated to be 188.77 m³/hr, while the existing HCFM operational capacity was only capable of supplying approximately 68.14 m³/hr. Similarly, the required water demand for foam operation decreased from 6,103.72 m³/hr under theoretical conditions to 2,203.10 m³/hr based on the existing HCFM operating capacity.

Consequently, the minimum firefighting discharge duration was adjusted from the standard 30 min to 83.12 min to maintain firefighting operations under the available HCFM capacity, as summarized in Table 3.

Table 3. Fire Water and Foam Demand Summary

Activity	Parameter	Theoretical Req. (m³/hr)	Existing Capacity (m³/hr)
Cooling	Adjacent tank cooling water demand	331.84	223.23
Fire fighting	Foam solution demand	188.77	68.14
	Water demand for foam operation	6,103.72	2,203.10
Fire fighting Duration	Minimum discharge time (min.)	30**	83.12
Total Demand	Total fire water demand		2,649.56
	Total foam demand		94.39*

**Total foam demand expressed as foam solution inventory requirement (m³).*
***Standard firefighting duration assumption prior to adjustment based on existing HCFM operating capacity.*

The discrepancy between theoretical firefighting requirements and existing operational capacity indicates that firefighting operations under the analyzed dike-on-fire scenario were constrained by the capability of the existing firefighting equipment. According to API RP 2030, cooling protection is required to reduce thermal radiation exposure and prevent fire escalation to adjacent tanks during hydrocarbon storage tank fire incidents. In addition, NFPA 11 emphasizes that adequate foam application rate and discharge duration are essential to maintain suppression effectiveness during flammable liquid fire scenarios.

The prolonged firefighting duration identified in this study also indicates significant operational challenges during emergency response activities. Kwon et al. (2021) reported that large-scale gasoline storage tank fires generate high heat release rates and prolonged burning durations, resulting in difficult firefighting operations and increased escalation potential. Similarly, Baser and Behnam (2020) explained that inadequate firefighting resources and delayed suppression capability may increase the probability of domino effect propagation within tank farm facilities. Therefore, the results obtained in this study highlight the importance of evaluating both firefighting demand and hydraulic capability to ensure adequate fire protection performance under large-scale dike-on-fire conditions.

Hydraulic Analysis of Existing Fire Water System

Hydraulic analysis was conducted to evaluate the capability of the existing fire water system in supplying the required firefighting demand under the analyzed dike-on-fire scenario. The hydraulic simulation was performed using the existing fire water network configuration consisting of fire pumps, ring main pipelines, hydrants, monitors, and foam systems installed within the gasoline tank farm area. Hydraulic simulation results were evaluated using gpm units following the operational fire water system and pump capacity configuration.

Figure 2 presents the hydraulic simulation model and pressure distribution within the existing fire water network under the analyzed dike-on-fire scenario. The simulation results indicated that the ring main system maintained stable pressure distribution throughout the tank farm area during simultaneous cooling and firefighting operations. Most hydrant nodes operated within operational pressure ranges, indicating that the existing fire water network was capable of supplying firefighting demand under the analyzed emergency condition.

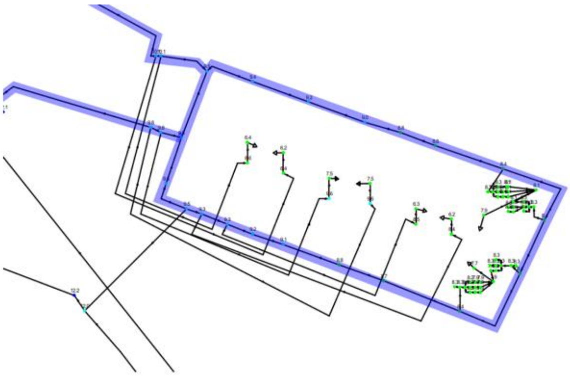

Figure 2. PIPENET Hydraulic Simulation Model

The hydraulic simulation results demonstrated that the existing fire water system was capable of supplying the required firefighting demand under the analyzed emergency scenario. Based on the hydraulic analysis results, the total available fire water flowrate supplied by the system reached approximately 13,017.50 gpm, exceeding the required firefighting demand of 11,665.68 gpm. In addition, the hydraulic simulation indicated that adjacent tank cooling operations for tanks D-320-07A and D-320-07C were supplied with flowrates of approximately 6,513.25 gpm and 6,504.25 gpm, respectively.

The hydraulic analysis also demonstrated that pumps G-33-01A, G-33-01B, and G-33-01C were operating during the analyzed firefighting scenario, while pump G-33-01D remained in standby condition. Furthermore, hydrant outlet hydraulic analysis showed that HCFE-01 and HCFE-02 delivered firefighting flowrates of approximately 5,808.2 gpm and 3,925.7 gpm with outlet pressures of 6.97 kg/cm²G and 7.17 kg/cm²G, respectively.

Table 4. Hydraulic Analysis Result

Parameter	Required Demand (gpm)	Hydraulic Analysis Result
Adjacent tank cooling (D-320-07A)	5,832.84	6,513.25
Adjacent tank cooling (D-320-07C)	5,832.84	6,504.25
Total fire water demand	11,665.68	13,017.50
HCFE-01 outlet pressure	-	6.97 kg/cm²G
HCFE-02 outlet pressure	-	7.17 kg/cm²G

The hydraulic simulation results indicate that the existing fire water system was capable of supplying the required firefighting demand during simultaneous cooling and firefighting operations under the analyzed dike-on-fire scenario. The total available firefighting flowrate exceeded the required firefighting demand, indicating that the existing fire water network was hydraulically capable of supporting emergency response operations within the analyzed tank farm area.

In addition, the hydraulic simulation demonstrated that hydrant outlet pressures remained within operational ranges during firefighting operations, indicating stable hydraulic performance throughout the fire water distribution network. According to API RP 2030, adequate hydraulic performance is essential to maintain continuous cooling protection and foam application effectiveness during hydrocarbon storage tank fire incidents.

Although the hydraulic network was capable of supplying the required firefighting demand, the prolonged firefighting duration identified in the firefighting demand analysis indicates that operational dependence on existing HCFM capacity remains an important consideration during emergency response planning. Sotoodeh (2023) also emphasized that reliable fire water systems and sufficient operational firefighting capacity are critical to reduce escalation potential and improve firefighting effectiveness in storage tank facilities.

This study was limited to the evaluation of the existing fire water system under a single dike-on-fire scenario involving gasoline storage tank D-320-07B at PT X Refinery. The hydraulic analysis was conducted using steady-state simulation based on the existing fire water network configuration, available pump capacity, and existing HCFM operational conditions during simultaneous cooling and firefighting operations. Therefore, the study did not evaluate transient hydraulic behavior, multiple simultaneous fire scenarios, or alternative fire protection system configurations under different emergency conditions.

Future studies are recommended to evaluate additional fire escalation scenarios and alternative firefighting system configurations to improve fire protection reliability in hydrocarbon storage tank facilities. Further hydraulic analysis under transient emergency conditions may also provide a more comprehensive evaluation of firefighting system performance during large-scale storage tank fire incidents.

CONCLUSION

This study evaluated the adequacy of the existing fire water system under a gasoline storage tank dike-on-fire scenario at PT X Refinery using PHAST consequence analysis and PIPENET hydraulic simulation. The PHAST simulation demonstrated that thermal radiation intensity of 12.5 kW/m² extended up to approximately 83 m from the fire source, indicating significant escalation potential affecting adjacent tanks located within the same bundwall area. Firefighting demand analysis showed that the total required fire water demand reached 11,665.68 gpm, while operational limitations of the existing HCFM capacity resulted in a prolonged minimum firefighting discharge duration of 83.12 min. Hydraulic simulation results demonstrated that the existing fire water system was capable of supplying the required firefighting demand during simultaneous cooling and firefighting operations, with the total available firefighting flowrate reaching 13,017.50 gpm under the analyzed emergency condition. However, the study also demonstrated that firefighting operations under large-scale dike-on-fire conditions remain highly dependent on the availability and operational capacity of the existing HCFM system. These findings indicate that although the existing fire water system was hydraulically capable of supporting emergency response operations for the analyzed scenario, improvement of firefighting system reliability and operational preparedness remains important to enhance fire protection performance in hydrocarbon storage tank facilities.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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