

Dynamic Assessment Of Fireball Geometry And Heat Flux From Large Scale Gasoline Releases In Storage Installations

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Abstract

Accidental release and ignition of gasoline in large storage tanks can result in devastating fireball events with significant thermal consequences. This study presents a dynamic modeling approach to assess fireball behavior and its associated heat flux under large-scale hydrocarbon storage scenarios. Using the Roberts Method, key fireball parameters—such as maximum diameter, duration, burning rate, and surface emitting power—were quantitatively determined for a 7389 m³ gasoline storage tank filled to 65% capacity. A comprehensive analysis was conducted to compute maximum and actual surface emitting power, followed by heat flux estimation at varying distances using view factor theory and atmospheric transmissivity. The fireball reached a diameter of 889.09 meters with a burn duration of 68.98 seconds and a maximum surface emitting power of 333.985 kW/m². Heat flux values exceeded 80 kW/m² within 100 meters, indicating severe thermal hazard zones. These findings serve as critical input for safety zoning, emergency planning, and fire protection design in petroleum storage facilities. The study emphasizes the necessity of predictive modeling tools for identifying high-risk areas and implementing mitigation strategies in flammable liquid storage environments.

Keywords: Fireball modeling, Thermal radiation, Heat flux, Roberts Method, Hydrocarbon storage, Safety assessment.

I. Introduction

The storage and handling of large volumes of gasoline pose inherent fire and thermal radiation risks in the event of an accidental release and ignition. Fireballs generated during such incidents produce extreme temperatures and radiant heat that can lead to fatalities, structural damage, and environmental degradation within seconds. Understanding fireball behavior specifically its geometry, duration, and radiative output is essential for establishing safe separation distances, designing fire protection systems, and formulating emergency response plans.

Traditional risk assessment techniques are often insufficient to capture the dynamic characteristics of fireballs. In this study, the Roberts Method is employed as a mathematical tool to estimate the key physical parameters of a fireball resulting from the ignition of a partially filled gasoline storage tank. The resulting fireball parameters such as diameter, height, duration, burning rate, and surface emitting power are used to evaluate thermal radiation exposure at varying distances. This predictive modeling approach enhances risk awareness, helps identify high-risk zones, and supports thermal hazard mitigation in hydrocarbon storage environments. The Objectives of the research are:

- To analyze fireball geometry from large-scale gasoline releases using Robert's method.
- To estimate burning rate and surface emitting power during combustion.
- To calculate view factor and radiant heat flux at various distances.

- To assess thermal impact on humans, structures, and environment.
- To define safety zones and aid in emergency planning.
- To support predictive modeling for fire risk in fuel storage facilities.

II. Literature review

The dynamic behavior of fireballs resulting from large-scale gasoline releases in storage installations has been a critical subject of study due to its implications for human safety, structural integrity, and emergency response planning. Fireball formation, geometry, duration, and associated thermal radiation pose severe threats in the event of hydrocarbon leaks and subsequent ignition. Quantitative and computational modeling efforts over the past decades have focused on understanding and predicting these parameters.

Qihong Wang et al. [1] demonstrated the effect of separation distances on vapor cloud dispersion and explosion using CFD tools, which serves as a foundation for defining safe zones around storage tanks. Similarly, Wei et al. [3] analyzed dust explosion hazards and radiation release, offering insights relevant to fireball behavior in open environments. Lee [12] applied quantitative risk assessment to LNG-FSRU processes, where high-pressure storage conditions can mimic those in gasoline tanks, emphasizing the importance of accurate thermal flux prediction. Studies by Tauseef et al. [13] and Abbasi et al. presented detailed case analyses of major tank farm explosions, correlating fireball size and energy release with real-world damage. The development of accident causation models, like the 24Model by Gui et al. [10], helps in identifying underlying factors contributing to fireball formation. Research by Grant et al. [14] emphasized integrating traditional accident models with predictive simulation, while Al-Shanini et al. [16] focused on flammable material modeling in process industries. Marmo et al. [9] and Zhu et al. [7] provided frameworks for understanding heat transfer, radiative energy, and the role of environmental factors in fire propagation. Experimental approaches, such as those by Wang et al. [11] and Zhang et al. [4], assessed burning behavior of hydrocarbon fuels under varying pressures, offering benchmarks for fireball radius and duration. The work of Ade et al. [6] and Xing et al. [5] addressed safety system design and urban accident modeling, demonstrating the integration of fire risk analysis into system-level safety strategies.

Finally, Das and Weinberg [20] refined flammable mass estimation for vapor cloud explosion modeling, which is crucial for calculating fireball mass and geometry. Their work, along with that of Rathnayaka et al. [21], supports the use of energy-based approaches such as the Roberts Method to evaluate fireball parameters like diameter, height, and thermal flux. These studies collectively inform the present research, which employs a deterministic approach to assess fireball geometry, burning rate, and surface emitting power for gasoline storage incidents. The resulting thermal radiation profiles help estimate exposure risk zones and contribute to improved design standards and emergency preparedness strategies.

III. Materials and Methods

Storage tanks are primarily classified into three types based on roof structure and containment design:

External Floating Roof Tank (EFRT): Designed as single or double deck pontoon roofs following API STD 650. Commonly used for volatile liquids but exposed to atmospheric conditions.

Fixed Roof Tank: Constructed with cone or dome-shaped roofs. Suitable for low-pressure storage, often with inert gas blanketing. Designed per API STD 650 or 620.

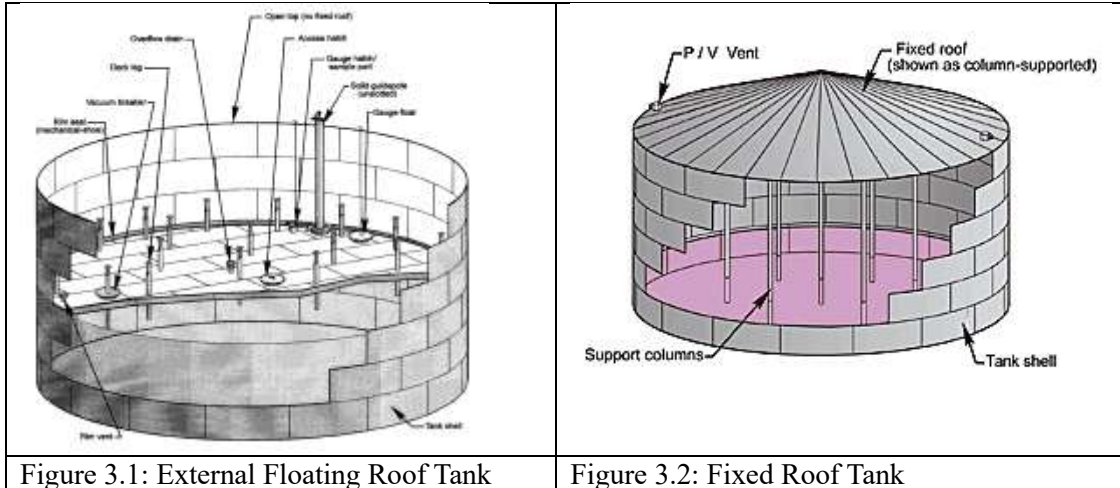


Figure 3.1: External Floating Roof Tank

Figure 3.2: Fixed Roof Tank

Internal Floating Roof Tank (IFRT): Combines a fixed roof with a floating deck. Preferred for reduced vapor losses and designed per API STD 650 or IS 803.

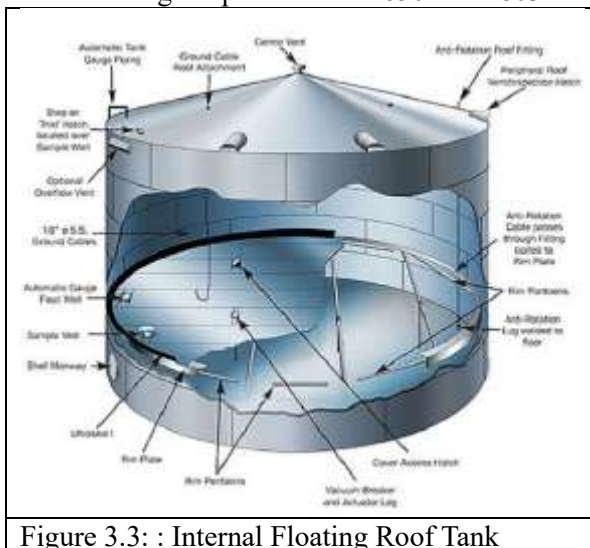


Figure 3.3: : Internal Floating Roof Tank

Selection of tank type depends on the product handled and site conditions. EFRTs with pan roofs are discouraged due to safety concerns.

Seal Requirements:

EFRTs and IFRTs must have double seals with $\geq 96\%$ vapor recovery.

Primary seal: Shoe/liquid-mounted (EFRT), vapor-mounted (IFRT).

Secondary seal: Rim-mounted.

Seal gaps are limited to ensure minimal vapor escape.

IV. Methodology

This study applies a quantitative approach to evaluate fireball hazards from accidental gasoline releases in bulk storage tanks. It integrates thermodynamic calculations, Roberts empirical modeling, and heat flux estimation to assess fireball size, duration, and thermal impact. The methodology enables prediction of hazard zones affecting humans, equipment, and the environment, aiding in risk mitigation and emergency planning.

A. Heat Release Rate Analysis

The heat release rate (HRR) is a critical factor in understanding fire dynamics. It is derived from the first law of thermodynamics for an open system and represents the energy released per unit time during combustion:

$$dQ_c = du + w + dQ_h$$

Where, dQ_c - heat release due to combustion of hydrocarbon fuel, dQ_h - heat transfer from combustion chamber to wall, du - the internal energy change and w - Work output. The simplified form for HRR is:

$$q_{Hc} = \Delta H_c \times m_{fuel}$$

Where, q_{Hc} = the heat release rate (kJ/s), ΔH_c = the heat of combustion (MJ.kg⁻¹), and m_{fuel} = the mass flow rate of the fuel (g/s). This calculation is essential for estimating the energy intensity of the fire scenario.

B. Quantitative Risk Assessment (QRA)

QRA is employed to assess the probability and consequence of potential explosion hazards:

1. Set the Context – Define the specific plant or storage area under assessment.
2. Risk Identification – List potential explosion or fire sources.
3. Risk Consequence Evaluation – Determine potential human, equipment, or environmental losses.
4. Likelihood Estimation – Use historical data and site conditions.
5. Risk Classification – Use the formula: Risk = C x L x E...
Where, C = consequence, L = likelihood, and E = exposure.
6. Prioritization – Identify high-CLE score risks.
7. Control Analysis – Propose mitigation or prevention strategies.
8. Action Plan – Define control implementation measures.
9. Communication Strategy – Identify stakeholders and communication pathways.
10. Review – Periodically update the risk profile and controls.

C. Scenario: Fireball Explosion Modeling

This scenario investigates the thermal consequences of a fireball generated by a Boiling Liquid Expanding Vapor Explosion (BLEVE). The analysis follows a systematic approach that includes:

- Estimating the quantity of flammable material based on the tank's volume and fuel density
- Applying the Roberts Method to predict the fireball's maximum diameter and duration
- Calculating the burning rate to understand combustion dynamics
- Determining both the maximum and actual surface emitting power of the fireball
- Evaluating the view factor and resulting radiative heat flux at varying distances from the explosion center

This study uses thermophysical data and empirical equations to model fireball behavior and assess the potential thermal impact on nearby personnel, equipment, and infrastructure in the event of a catastrophic release from a gasoline storage tank.

1. Initial Conditions and Input Data

A vertical cylindrical tank with a total capacity of 7389 m³ was considered, containing 65% gasoline (motor spirit). The key physical and thermodynamic properties are:

- Density of gasoline (ρ): 750 kg/m³
- Heat of combustion (ΔH_c): 47300 kJ/kg
- Storage pressure (P_{sv}): 1.5 MPa
- Ambient temperature (T_a): 298.15 K
- Atmospheric transmissivity (τ_a): 1 (assuming clear atmosphere)

The total mass of gasoline (M) was calculated using:

$$M = f V \rho_{mat} M = .65 * 7389 * 750 M = 3602137.5 \text{ kg}$$

2. Fireball Parameter Estimation (Roberts Method)

The Roberts Method was used to estimate the fireball diameter, duration, and center height, employing the following empirical correlations:

- Maximum Fireball Diameter (D_{max}):
 $D_{max} = 5.8 M^{1/3} = 889.09\text{m}$
- Total Fireball Duration (T_{max}):
 $T_{max} = 0.45 M^{1/3} = 68.98\text{s}$
- Height of Fireball Center (H): $H = D_{max} = 889.09\text{ m}$

3. Burning Rate

The burning rate per unit area was computed using the formula:

$$m' = \frac{M}{(0.888\pi D_{max}^2) t_{max}} = 0.023\text{ kg/m}^2\text{s}$$

4. Surface Emitting Power

• Maximum Surface Emitting Power (SEP_{max}) was calculated using:

$$F_s = c_6 P_{sv}^{0.32} = 0.307$$

$$F_s = 0.307, m' = 0.023\text{ kg/m}^2\text{s}, \Delta H_c : 47300\text{ kJ/kg}$$

$$SEP_{max} = 333.985\text{ kW/m}^2$$

- Actual SEP (SEP_{act}) was assumed equal to SEP_{max} 333.985kW/m²

5. View Factor (F_{view})

The view factor between the fireball and an observer at a horizontal distance 'a' was calculated using:

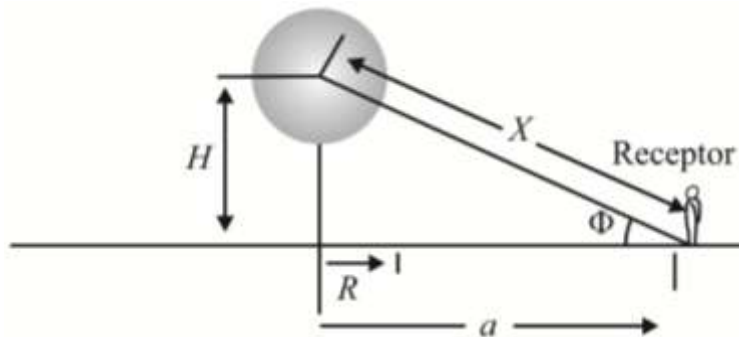


Figure 4.1: Geometric Representation of Fireball Radiation Exposure to a Receptor

$$F_{view} = \left(\frac{R}{X}\right)^2$$

$$X = \sqrt{H^2 + a^2}$$

Where $R = D_{max}/2 = 444.54\text{ m}$.

6. Radiant Heat Flux Estimation

The incident thermal radiation or **heat flux (q')** was estimated using:

$$SEP_{act} = 333.985\text{ kw/m}^2, \text{ atmospheric transmissivity } \tau_\alpha = 1.$$

$$q' = SEP_{act} F_{view} \tau_\alpha$$

Given $\tau_\alpha = 1$, the heat flux at varying distances is:

Table 4.1: Heat Flux vs. Distance from Fireball

Real distance from the fire ball (m)	$X = \sqrt{H^2 + a^2}$	View Factor: $F_{view} = (R/X)^2$	Heat Flux: $q' = SEP_{act} F_{view} \tau_\alpha$ kW/m ²
50	890.49	0.249	83.161
100	894.69	0.246	82.159
200	911.30	0.237	79.153
500	1020.03	0.189	63.122

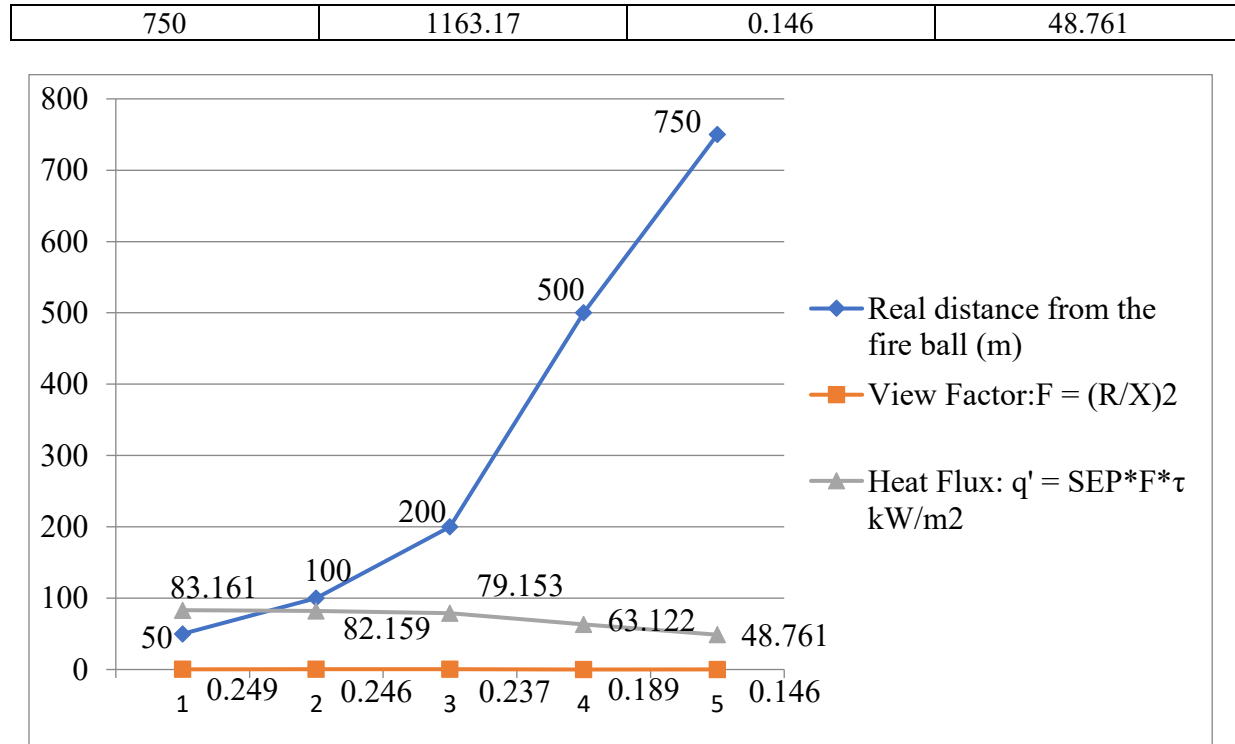


Figure 4.2: Relation between different distance, view factor and heat flux

V. Results

The fireball scenario resulting from a BLEVE-type explosion was analyzed using the Roberts Method to quantify thermal radiation effects from a large-scale gasoline storage tank incident.

1. Total Mass of Fuel Involved:
The storage tank, filled to 65% of its 7389 m³ capacity, resulted in a total fuel mass of 3,602,137.5 kg.
2. Fireball Characteristics (Roberts Method):
 - Maximum Diameter (D_{max}): 889.09 m
 - Fireball Duration (T_{max}): 68.98 seconds
 - Height of Center of Fireball (H): 889.09 m
3. Burning Rate: Estimated at 0.023 kg/m²·s, indicating sustained and intense combustion over a large surface area.
4. Maximum Surface Emitting Power (SEP_{max}): 333.985 kW/m², reflecting the thermal intensity of the fireball.
5. Heat Flux at Different Distances: Using view factor geometry and assuming atmospheric transmissivity of 1, the incident heat flux at different distances from the fireball center was calculated as:
 - At 50 m: 83.16 kW/m²
 - At 100 m: 82.16 kW/m²
 - At 200 m: 79.15 kW/m²
 - At 500 m: 63.12 kW/m²
 - At 750 m: 48.76 kW/m²

These heat flux levels far exceed human tolerance thresholds (typically ~37.5 kW/m² for third-degree burns and ~12.5 kW/m² for ignition of wood), indicating a severe threat to human life, equipment integrity, and combustible materials especially within a 200-meter radius.

The analysis emphasizes the need for strict hazard zoning, passive fire protection, and emergency evacuation planning in fuel storage installations.

VI. Conclusion

This study presents a comprehensive modeling approach for assessing fireball hazards resulting from large-scale gasoline tank releases. The Roberts Method provided an effective means to quantify fireball diameter, duration, burning rate, and radiant heat flux. The findings indicate that thermal radiation levels exceed critical safety thresholds within 200 meters, with heat fluxes above 80 kW/m² observed at close proximity. These values highlight the potential for severe burns, equipment ignition, and material failure.

The results emphasize the importance of predictive thermal radiation modeling in the planning and design phases of petroleum storage facilities. Incorporating fireball assessment into safety strategies ensures more accurate zoning of hazard areas, improved emergency response, and enhanced protection for workers and assets. Ultimately, this work supports the proactive prevention of thermal disasters in flammable liquid storage systems.

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