

Calculation and Comparison of Parameters during Fire in Large Capacity Crude Oil Storage Tanks

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Abstract

The heat release rate during a fire is an initial parameter for calculating average flame height. Average flame height is essential for subsequent calculations of heat flow density and also for setting separation distances. The article calculates and compares the values of these two basic parameters in a fire in three real, existing large-capacity tanks for the storage of crude oil. The stated calculations are for the two most difficult scenarios of five possible fire scenarios for above ground double-walled storage tanks with floating roofs. The calculations showed that increasing the diameter of the tank increases the flame height, but not in proportion, and above a certain threshold diameter of the tank remains virtually constant.

Keywords: Storage tank; Oil fire; Fire parameters; Heat release rate; Average flame height

Introduction

Ignitable liquids pose challenging problems for fire protection because they can readily initiate combustion, burn with high heat release rate (HRR), spread the flame rapidly, and are difficult to extinguish [1]. In the world, there are currently several types of large-capacity storage tanks for crude oil. Oil is stored in underground large-capacity bunkers or above ground in large-capacity containers and tanks. Individual liquefied gas petroleum or liquid petroleum products are stored similarly. In terms of their overall design and location we can divide large capacity over ground tanks into:

1. single wall steel tanks protected around the perimeter by an earth wall,
2. two or more single wall steel tanks protected by an earth wall,
3. single wall steel tanks protected by a reinforced concrete perimeter wall,

4. reinforced concrete tanks,
5. double wall storage tanks,
6. double wall storage tanks protected by an earth wall,
7. two or more wall storage tanks protected by an earth wall.

Depending on the type of roof we can divide large capacity tanks into:

1. open – without roof,
2. tank with a fixed roof,
3. tank with a floating roof [2].

Double wall large-capacity tanks in above-ground designs are of a vertical, cylindrical shape, welded from steel components, all-metal. They have a chamber-floating roof that floats on the surface of the stored liquid. The roof is also made from welded steel components. The air chambers created enable the roof to float on the surface of the stored liquids. In the case of crude oil ignition, the rapid spread of fire and intense combustion can be

expected. The fire spreads across the surface of the flammable liquid over its whole area. Oil has a high calorific value and flame temperature in which fire reaches up to 1,400°C [3].

Iwata in testing 14 kinds of oil in a conical calorimeter we found a correlation between HRR and density, whereby at a higher density of oil, HRR fell [4]. The flame height (L_f) depended on the cylindrical diameter (D) and the ratio of L_f/D decreases with increasing the diameter of the tank [5]. Large-scale pool fires have been studied in great detail for several decades. The extensive work on hydrocarbon based fuels is based on a number of large scale tests including fuels like gasoline, crude oil, kerosene and ethanol [5-10].

A series of well-defined parameters have been established to classify pool fires in a quantitative manner. Despite the enormous body of work on large-scale pool fires there are still significant uncertainties in our understanding of such fires and capabilities to predict their behaviour. There is a critical need for more well-instrumented experimental studies, as well as further development and validation of detailed numerical models. In fire protection engineering, there is a need to extend models for predictions of fire behaviour to large scale fire scenarios [11,12].

The aim of the paper was therefore to calculate and compare the heat release rate and the height of flame in a fire in selected large-capacity tanks for storing crude oil.

Experimental Part

Methodology of Calculation

Calculation of parameters in a fire was undertaken for selected sizes of large-capacity tanks, which are currently in operation in Slovakia and the Czech Republic. The selected tanks by design and build are very similar. However, during the work, we focused on the impact of their different dimensions of heat release rate of fire and average flame height.

Fire Scenarios: In double wall above-ground storage tanks, where between the containment and storage tanks there is an area to capture the total amount of oil storage (interstice) it is necessary to consider several possible scenarios of fire:

1. Fire in the space between the roof of the tank and the wall of the tank – scenario S1
2. Fire in the containment tank and the space between the roof and the wall of the tank – scenario S2
3. Fire in the storage tank – whole area (in the event of the floating tank roof sinking) – scenario S3

4. Fire in the tank and containment tank (sunken roof of the storage tank and damaged wall of the storage tank) S4
5. Fire in the containment tank (interstitial fire) S5

A damaged storage tank is the most difficult scenario in which fire affects the entire total area of the interstice and the area of the storage tank. For simplification, the horizontal surface is calculated using the diameter of the emergency tank, which is the sum of the areas of the storage tank and the interstice. Baseline for our calculations and subsequent comparison will be Scenarios S3 and S4.

Parameters during Fire

Heat release rate during fire (Q^):*

Heat released per unit of time ($\text{kJ}\cdot\text{s}^{-1}$), which changes with time.

- for a natural fire in the tanks the speed becomes constant,
- it depends on the diameter of the tank D ,
- for a diameter above 0.2 m the rate of combustion by area increases with the diameter to a defined value, after which it is constant,
- it depends on the constant $k \times \beta$ the product of the radiation flow characteristic for the fuel (tabulated for liquids and thermoplasts).

In the case of crude oil combustion in large capacity tanks, we expect the fire to be governed by fuel, insofar as the access of air into the fire zone should not be limited in any way.

We calculate the heat release rate as:

$$Q^* = A_f \times m_\infty'' \times (1 - e^{-k \times \beta \times D}) \times \chi \times \Delta H_c \quad (1)$$

A_f - horizontal combustion area (m^2)

m_∞'' - rate of combustion by area ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), for crude oil = ($0.02833 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)

$k \times \beta$ - product of constant radiation flow from the flame and the surface of the flammable liquid (2.8 m^{-1})

D - diameter of tank (m)

χ - efficiency of combustion (%), for crude oil = (70 % i.e. 0.7)

ΔH_c - total heat of combustion ($\text{kJ}\cdot\text{kg}^{-1}$), for oil = ($42.5 \text{ MJ}\cdot\text{kg}^{-1} = 42,500 \text{ kJ}\cdot\text{kg}^{-1}$)

Average height of flame (L_f):

Averaging the height of the luminous flame over time, y (appearance of a flame) 1.0 stable flame, 0.5 in the middle of the time, at horizontal distance L (m) from the flame is found experimentally from video recordings - conformance with subjective visual perceptions.

Correlation of flame height – the reason is the turbulent nature, dependence on the area of combustion D and heat release rate Q' .

We calculate the average height of flame [13]:

$$L_f = 0.235 \times Q'^{\frac{2}{5}} - 1.02 \times D \quad (2)$$

Storage tank with a volume of 30,000 m³ (cross section and parameters are in (Figure 1)) – calculation:

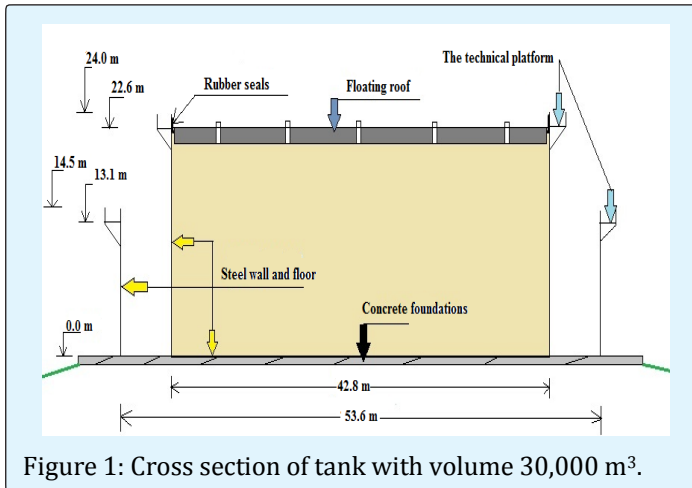


Figure 1: Cross section of tank with volume 30,000 m³.

D – diameter of tank (42.8 m)

D_h – diameter of containment tank (53.6 m)

A_f – horizontal combustion area of tank (1,439 m²)

A_{fh} – horizontal combustion area of containment tank (2,256 m²)

m''_{∞} – rate of combustion by area (0.02833 kgm⁻²s⁻¹)

$k \times \beta$ – product of constant radiation flow from the flame to the surface of the flammable liquid (2.8 m⁻¹)

χ – efficiency of combustion of crude oil (70 % i.e. 0.7)

ΔH_c – total heat of combustion of crude oil (42.5 MJkg⁻¹ = 42,500 kJkg⁻¹)

Values used in the calculation were taken from literature [13].

$$Q' = A_f \times m''_{\infty} \times (1 - e^{-k \times \beta \times D}) \times \chi \times \Delta H_c \quad (\text{kJ s}^{-1})$$

$$Q' = 1,439 \times 0.02833 \times (1 - e^{-2.8 \times 42.8}) \times 0.7 \times 42,500 = 1,212,814.4 \text{ kJ s}^{-1} = 1,212.8144 \text{ MW}$$

For fire in a large capacity tank with a volume of 30,000 m³ the heat release rate is approximately 1,213 MW.

The average flame height during the fire L_f :

$$L_f = 0.235 \times Q'^{\frac{2}{5}} - 1.02 \times D \quad (\text{m})$$

$$L_f = 0.235 \times 1,212,814.4^{2/5} - 1.02 \times 42.8 = 20.1 \text{ m}$$

The average flame height during the fire is approximately 20.1 m

Storage tank with a volume of 70,000 m³ (Figure 2) – calculation:



Figure 2: Storage tank with volume of 70,000 m³.

D – diameter of tank (66 m)

D_h – diameter of containment tank (80 m)

A_f – horizontal combustion area (3,421 m²)

A_{fh} – horizontal combustion area of containment tank (5,027 m²)

m''_{∞} – rate of combustion by area (0.02833 kgm⁻²s⁻¹)

$k \times \beta$ – product of constant radiation flow from the flame to the surface of the flammable liquid (2.8 m⁻¹)

χ – efficiency of combustion of crude oil (70 % i.e. 0.7)

ΔH_c – total heat of combustion of crude oil (42.5 MJkg⁻¹ = 42,500 kJkg⁻¹)

$$Q' = 3,421 \times 0.02833 \times (1 - e^{-2.8 \times 66}) \times 0.7 \times 42,500 = 2,883,278.7 \text{ kJ/s} = 2,883.2787 \text{ MW}$$

For fire in a large capacity tank with a volume of 70 000 m³ the heat release rate is approximately 2,883 MW.

The average flame height during the fire L_f :

$$L_f = 0.235 \times 2,883,278.7^{2/5} - 1.02 \times 66 = 22.84 \text{ m}$$

The average flame height during the fire is approximately 22.84 m.

Storage tank with a volume of 125,000 m³ (Figure 3) – calculation:

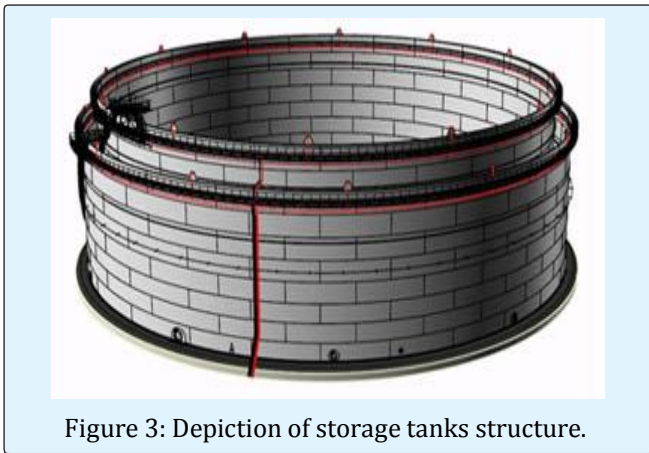


Figure 3: Depiction of storage tanks structure.

D – diameter of tank (84.47 m)

D_h – diameter of containment tank (90.47 m)

A_f – horizontal combustion area of tank (5,604 m²)

A_{fh} – horizontal combustion area of containment tank (6,428 m²)

m''_{∞} – rate of combustion by area (0.02833 kgm⁻²s⁻¹)

$k \times \beta$ – product of constant radiation flow from the flame to the surface of the flammable liquid (2.8 m⁻¹)

χ – efficiency of combustion of crude oil (70 % i.e. 0.7)

ΔH_c – total heat of combustion of crude oil (42.5 MJkg⁻¹ = 42,500 kJkg⁻¹)

$Q' = 5,604 \times 0.02833 \times (1 - e^{-2.8 \times 84.47}) \times 0.7 \times 42,500 = 4,723,149.3 \text{ kJs}^{-1} = 4,723.1493 \text{ MW}$

For fire in a large capacity tank with a volume of 125,000 m³ the heat release rate is approximately 4,723 MW.

The average flame height during the fire L_f :

$L_f = 0.235 \times 4,723,149.3^{2/5} - 1.02 \times 84.47 = 23.68 \text{ m}$

The average flame height during the fire is approximately 23.68 m.

Results and Discussion

Table 1 shows the theoretical volume of the tank as well as real calculated volumes from the known dimensions of the tank and the maximum storage level of the oil. For each scenario (S3 and S4), the heat release rate during the fire and flame height of the flame during the fire is also stated.

These parameters are compared in selected large-capacity tanks.

Storage tank volume (m ³)	30,000		70,000		125,000	
Calculated storage tank volume (m ³)	29,062		72,803		124,968	
Scenario	S3	S4	S3	S4	S3	S4
Diameter (m)	42.8	53.6	66	80	84.47	90.47
Area (m ²)	1,439	2,256	3,421	5,027	5,604	6,428
Q' (MW)	1,213	1,901	2,883	4,237	4,723	5,418
L_f (m)	20.1	21.65	22.84	23.57	23.68	23.76

Table 1: Comparison of calculated parameters for selected scenarios.

From the compared values for heat release rate during a fire it follows that the heat release rate during a fire is directly proportional to the area of the fire (Figure 4).

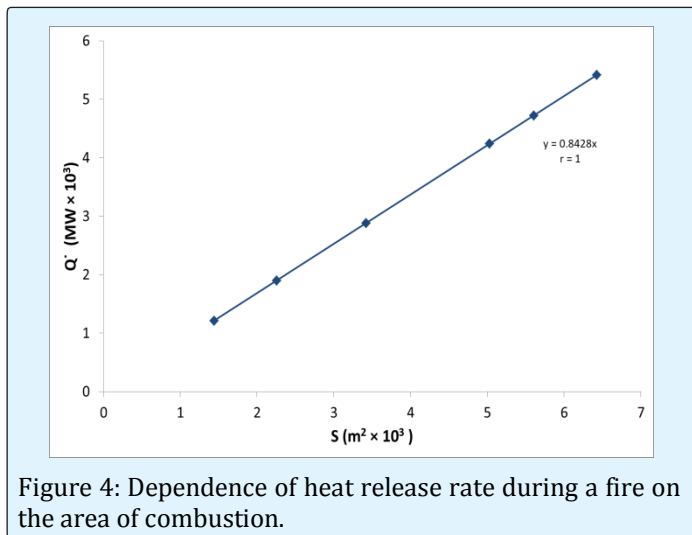


Figure 4: Dependence of heat release rate during a fire on the area of combustion.

In the case of a fire in selected large-capacity tanks, we used the total horizontal surface of oil stored as the area of the fire. We found, for three selected tanks under two scenarios, the heat release rate was constant in terms of energy per unit of time per unit area with a value of $q''_f = \text{kWm}^{-2}$ (0.8428 MWm⁻²) for oil with the stated characteristics. Baum and McGrattan report for a large storage tank of oil (with a mean of 84 m and height 27 m) the heat release rate during the fire is 4.7 GW, which when converted to a heat release rate per area comes to approximately $q''_f = \text{kWm}^{-2}$ (0.848 MWm⁻²), which corresponds well with our results [14]. With wind of 6 ms⁻¹ (at a height of 27 m above ground) an outside temperature of 20°C, they state the rate of energy release by area during a fire in the oil tank as $q''_f = 1,000 \text{ kWm}^{-2}$ (1 MWm⁻²). After deducting the shielding of the flame by smoke during the crude oil fire, (we assume 10% shielding), the rate of release of energy by area $q''_f = 900$

kWm^{-2} (0.9 MWm^{-2}). McGrattan gives, for crude oil, a rate of energy release by area of $q_f'' = 1,900 \text{ kWm}^{-2}$, whereby they assume a rate of combustion by area for crude oil of $m''_{\infty} = 0.045 \text{ kgm}^{-2}\text{s}^{-1}$, with a total heat of combustion of $\Delta H_c = 42,600 \text{ kJkg}^{-1}$ and efficiency of combustion of $\chi = 1$ (100 %) [15]. In the paper we assumed a combustion rate per area of $m''_{\infty} = 0.028 \text{ kgm}^{-2}\text{s}^{-1}$, with a total heat of combustion of $\Delta H_c = 42,500 \text{ kJkg}^{-1}$ and effectiveness of combustion of $\chi = 0.7$ (70 %). Considering that we assumed a significantly lower rate of combustion and efficiency of combustion, the heat release rate per area was lower than that of the state authors by 55%.

In comparing the average flame height for a fire between tanks and scenarios, there are only differences in the order of several centimetres to decimetres. The largest difference (1.55 m) is between the scenarios with a $30,000 \text{ m}^3$ capacity tank, the smallest difference (8 cm) is seen between the scenarios with a $125,000 \text{ m}^3$ capacity tank. Figure 5 shows that enlarging increases flame height, but not in direct proportion above a certain threshold of tank diameter (in our case approximately 80 metres) it remains practically constant.

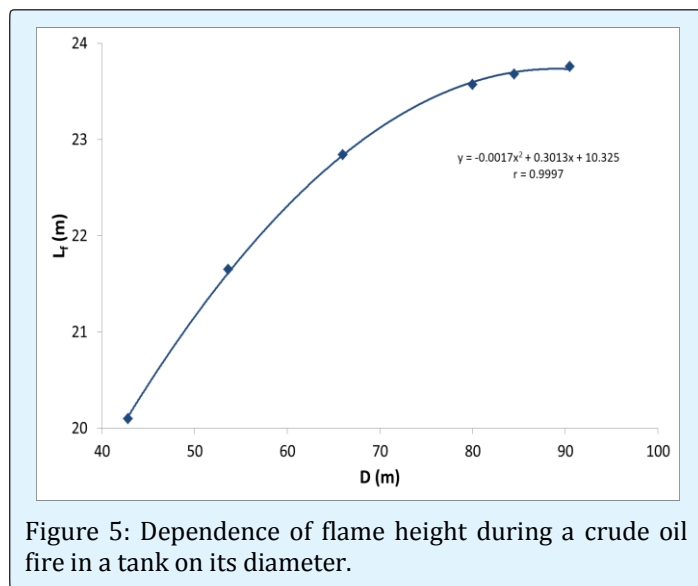


Figure 5: Dependence of flame height during a crude oil fire in a tank on its diameter.

With a natural fire in tanks, the heat release rate during a fire becomes a constant, for a diameter over 0.2 m, the combustion rate by area increases with the diameter to the stated value, after which it is constant m''_{∞} [13,16]. The values of m_{∞} and k' were obtained for diesel oil and gasoline by various authors [17,18]. This allowed prediction of the burning rate as a function of pool diameter; the agreement between the calculated values and the experimental results was quite good.

Conclusions

Parameters were calculated for a fire in three different dimensions of tanks in the most difficult selected scenarios. Generally, it would suffice for large capacity tanks from a certain diameter to calculate using a constant heat release rate during a fire per unit time per unit area of oil storage with the same characteristics. Also, for other flammable liquids there should be a constant release of energy per unit time per unit area proportional to the total combustion heat, rate of combustion by area, combustion efficiency and the constant product of radiation flow from flame to the surface of the flammable liquid.

In the calculated values, an average flame height was found considering the relation between the diameter and volume of the selected tanks to deviate from a few centimetres to tens of decimetres. For each tank, the average flame height was over 20 m. These values may be calculated only without wind, the effect of wind and other unexpected situations such as squirting, boiling, deformation of tanks, or breach of the floating roof could increase flame height several-fold.

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