

# Determining the Relationship Between the Parameters Time to Boilover and Mass Burning Rate with the Prevention and Response Strategies in Petroleum Product Storage Tank Fires

Evgeniy Ivanov

Faculty of Fire Safety and Civil Protection  
Academy of the Ministry of Interior Sofia, Bulgaria  
[evgivanov@amvr.bg](mailto:evgivanov@amvr.bg)

Stefan Parvanov

Faculty of Fire Safety and Civil Protection  
Academy of the Ministry of Interior Sofia, Bulgaria  
[sip\\_81@abv.bg](mailto:sip_81@abv.bg)

**Abstract-** The phenomenon of “boilover” in storage tanks containing petroleum products is among the most hazardous events that can occur during large-scale fires. When water is present at the bottom of the tank, the burning hydrocarbon layer may cause a sudden evaporation of the water, followed by a violent ejection of hot liquid and a massive fireball. This scenario poses severe threats to personnel safety, facility integrity, and environmental protection. Given the increasing global demand for petroleum-based fuels and the continued use of large above-ground storage tanks, understanding and mitigating the risks associated with boilover has never been more critical. The primary objective of this study is to clarify how two key parameters - time to boilover and mass burning rate - influence both prevention and response strategies during petroleum product tank fires. The research employs a combination of experimental data analysis and critical literature review to assess how these parameters correlate with the escalation of fire events. The experiments, conducted under controlled laboratory conditions, measured the influence of fuel properties, water layer thickness, and burning surface area on boilover onset and burning intensity. Based on these findings, the study synthesizes the most applied structural (e.g., tank design, insulation, drainage systems) and operational (e.g., cooling tactics, fuel-level monitoring, emergency response timing) fire protection strategies. Emphasis is placed on how real-time assessment of the mass burning rate and the predicted time to boilover can inform decision-making during emergencies. The results show that the earlier identification of critical thresholds significantly enhances the effectiveness of intervention measures. Moreover, certain prevention methods - such as early cooling and drainage - can delay or even prevent boilover if applied in a timely manner. Ultimately, this study bridges the gap between theoretical fire behavior parameters and practical fire safety management, offering a more

predictive and data-driven approach to handling storage tank fires.

**Keywords:** *boilover, prevention and response, mass burning rate, time to boilover.*

## I. INTRODUCTION

Petroleum product storage tanks are essential for industrial operations, yet they present significant fire safety hazards, particularly the phenomenon known as *boilover*. Boilover is a violent event resulting from the rapid vaporization of a water layer beneath a burning fuel, leading to a sudden ejection of hot liquid and a massive fireball [1], [2].

This phenomenon severely threatens personnel safety, environmental integrity, and critical infrastructure.

The increasing storage and industrial use of alternative fuels, edible oils, and essential oils further elevate these risks due to their distinct thermophysical properties compared to traditional petroleum products [3], [4].

Previous studies have categorized boilover into thin-layer and deep-layer events, where thin-layer boilover occurs with fuel layers below 10 mm and deep-layer boilover with thicker fuel deposits [5], [6]. While thin layers can lead to rapid ignition and spread, deep-layer fires can accumulate significant thermal energy, culminating in explosive boilover.

The fundamental works of [6] and [7] established that the development of a “hot zone” within the fuel layer and the heat conduction toward the water layer are critical factors leading to boilover. Subsequent experiments conducted by researchers such as [4], [8] have emphasized the relevance of the mass burning rate and the temperature

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gradients within the fuel to predict the onset of this phenomenon.

Despite considerable progress, most existing models focus on one-dimensional heat conduction and neglect the complex multicomponent composition of biofuels and vegetable oils [9], [10].

Moreover, empirical correlations proposed by [2] and experimental observations by researchers like [11] point out the limitations of generalizing data obtained from crude oil fires to other fuels.

This study aims to experimentally and theoretically investigate the relationship between two critical parameters **mass burning rate** and **time to boilover** for various classes of combustible liquids, including petroleum products, biofuels, edible oils, and essential oils. By analyzing the dynamics of heat and mass transfer, as well as the development of the “hot zone” within the fuel layer, this research seeks to create predictive models capable of assessing boilover risks in a wide variety of industrial conditions.

Building upon the experimental work and theoretical models described in prior literature [7], [6], [4], [8], [5] the present research develops an integrated framework linking experimentally determined burning rates and boilover times to preventive and emergency response strategies. Ultimately, the findings aim to contribute to safer storage system designs, improved firefighting protocols, and risk management practices.

## II. MATERIALS AND METHODS

### A. Time to boilover

The time to boilover ( $t_b$ ) represents the interval between the ignition of the fuel and the sudden ejection of hot liquid when the water at the bottom reaches a critical temperature. A simplified conceptual model often used in literature [12] is:

$$t_B = \frac{\rho_1 c_p h_{HC} (T_{HW} - T_a)}{Q_f - \dot{m} [\Delta h_v + c_p (T_{0av} - T_a)]} \quad (1)$$

where:

$\rho_l$  - fuel density at the temperature  $T_a$  ( $\text{kg/m}^3$ );

$C_p$  - specific fuel temperature  $T_a$  ( $\text{kJ/kg K}$ );

$h_{HC}$  - initial fuel tank thickness before start of fire (m);

$\dot{m}$  - mass burning rate ( $\text{kg/m}^2 \text{ s}$ );

$\Delta h_v$  - temperature for start of evaporation  $T_a$  ( $\text{kJ/kg}$ );

$T_a$  - ambient temperature (K);

$T_{HW}$  - temperature of Heat wave during boilover (K).  
 $T_{HW}$  can be derived from fuel-distillation curves.

In simplified form, the equation has the following form:

$$t_B = \frac{\rho_f c_p h_f}{\dot{q}_T} \quad (2)$$

where:

$\rho_f$  - density of the fuel;

$c_{p,f}$  - specific heat capacity of the fuel;

$h_f$  - fuel layer thickness;

$\dot{q}_T$  - net heat flux or thermal transfer rate reaching the bottom layers.

### B. The mass burning rate

After analyzing literary sources [13] [14] the mass burning rate ( $\dot{m}$ ) can be defined as:

$$\dot{m} = \frac{dm_f}{A dt} \quad (3)$$

where:

$m_f$  - mass of the fuel;

$t$  - time;

$A$  - surface area of the fuel layer.

The negative sign highlights the reduction in fuel mass over time. A higher  $\dot{m}$  implies a more intense fire and a faster buildup of heat within the tank. However, the relationship between  $\dot{m}$  and  $t_b$  can be influenced by numerous parameters, including fuel composition, moisture content, and tank geometry.

## III. RESULTS AND DISCUSSION

The preliminary experimental data used in this study is summarized in Fig. 1. It includes:

- fuel type (diesel fuel, motor oil);
- experimental time to boilover (compared to two correlation-based predictions);
- heat wave propagation rate;
- mass burning rate ( $\dot{m}$ )
- temperature of boilover occurrence.

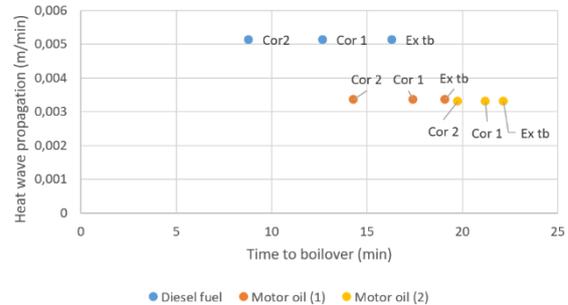


Fig. 1. Preliminary experimental data.

### A. Key observations

Drawing on the data presented in Fig. 1, several essential observations emerge regarding the behavior of different fuels and their corresponding boilover dynamics.

*a) time to boilover*

The experimental time to boilover for Diesel Fuel is measured at 16.3 minutes, whereas Correlation 1 predicts 12.68 minutes and Correlation 2 suggests 8.8 minutes. This discrepancy highlights those experimental conditions (fuel composition, ambient temperature, initial water layer thickness, tank geometry) can lead to significantly different outcomes than theoretical or semi-empirical models. Diesel, being relatively more volatile than heavier oils, can heat up the water layer quicker. However, external factors (e.g., wind, tank insulation, or the formation of a partial foam due to combustion byproducts) may delay the actual onset of boilover compared to simplified models. The first sample of motor oil exhibits a boilover time of 19.1 minutes, which is only moderately higher than the predicted 17.42 minutes (Correlation 1) but substantially longer than 14.29 minutes (Correlation 2). These figures suggest that the fuel's higher viscosity and lower volatility, compared to diesel, slow the overall heat penetration. The second sample shows the longest measured time to boilover at 21.2 minutes, aligning closely with one correlation (22.17 minutes) and slightly exceeding the other (19.76 minutes). The relatively better match might indicate that the correlation used for 22.17 minutes was calibrated to fuels with similar physical properties.

Together, these findings confirm that heavier, more viscous fuels (such as motor oil) may yield a longer time to boilover, yet the margin between experimental and predicted values can vary considerably depending on fuel-specific parameters.

*b) discrepancies between experimental and correlation values*

In some cases, Correlation 1 is closer to the experimental result (e.g., Diesel at 12.68 vs. 16.3 minutes) than Correlation 2 (8.8 vs. 16.3 minutes). However, for Motor Oil 1 or 2, the reverse scenario can occur.

These discrepancies can arise from assumptions about uniform heat flux, constant burning rate, or simplified water layer behavior in the models. Additionally, minor differences in initial conditions – such as water salinity, micro-emulsions, or tank wall thickness – can lead to significant variability in real experiments.

*c) Heat Wave Propagation Speed*

Measured at 0.00513 m/min in the diesel fuel layer, indicating a moderate rate of thermal penetration. Although this could cause the water layer to reach boiling in a relatively short timeframe, the actual event (16.3 minutes) was somewhat delayed, possibly due to environmental cooling or partial foam formation on the surface.

Both samples of motor oil exhibit lower heat wave propagation speeds, around 0.0033 m/min, reflecting the higher viscosity of motor oil. This slower progression of the thermal front can postpone boilover onset, which partly explains the longer times to boilover observed experimentally (19.1 and 21.2 minutes). Even with a slower heat wave, if the bottom water layer remains trapped and

eventually reaches a critical temperature, the ensuing boilover can still be severe. The longer heat accumulation period may also allow more time for intervention measures – yet, if no intervention occurs, the ultimate boilover event can be dramatic.

*d) Mass Burning Rate ( $\dot{m}$ )*

Diesel Fuel: 0.014 g/m<sup>2</sup>·s

Motor Oil (1): 0.050 g/m<sup>2</sup>·s

Motor Oil (2): 0.284 g/m<sup>2</sup>·s

These values reveal significant variability even among “similar” fuels (two samples of motor oil). Such differences highlight the importance of specific fuel characteristics, including the presence of additives, contaminants, or differing moisture content. A higher mass burning rate typically implies more rapid heat release; however, the corresponding time to boilover does not decrease at a strict linear proportion. Factors such as tank geometry, water distribution, and potential surface crusting or partial foam formation can alter the dynamics.

Practical implications of safety measures in petroleum fire scenarios stress the necessity of tailored strategies. The design and establishment of specific safety thresholds involve the creation of an equation to determine the possible fire extinguishing interval based on various dependencies. Each type of petroleum product may require its own calibrated correlation or monitoring approach to ensure that safety protocols are accurate and reflective of the distinct properties of different fuels. This necessitates continuous verification of these safety measures through regular validation against live or pilot-scale testing to prevent reliance on potentially inadequate emergency plans that are based on a single correlation if conditions deviate from those initially assumed.

A multimodal approach is advocated by some fire safety experts, who suggest combining multiple correlations and then comparing real-time data to both, using the most conservative estimate to trigger an early response. Thermal monitoring plays a critical role, especially the deployment of thermocouples at various depths to detect the gradual rise in temperature, which is particularly important for heavier oils. For these fuels, fire crews might gain extra minutes to apply foam or cooling measures before a boilover occurs, emphasizing the importance of robust early detection systems to capitalize on this extended intervention window.

In practice, adaptive foam application strategies require operators to adjust foam concentration and application rates according to the observed burning rate. Heavier fuels might need more robust or sustained foam coverage to effectively manage the fire. Additionally, knowing the variability in burning rates helps emergency planners in allocating resources more efficiently, estimating the quantity of firefighting media needed under worst-case scenarios [15], [16].

Such detailed understanding and adaptable responses are critical in enhancing safety protocols and ensuring preparedness in facing the dynamic challenges of petroleum fires.

*B. Strategies for Prevention and Response*

Building on these data-driven insights, the strategies for prevention and response to potential petroleum fires are intricately designed to tackle specific challenges through various proactive and reactive measures. The prevention strategies focus on controlling the water layer and constructive measures. Regular drainage is emphasized to minimize water accumulation at the tank's bottom, which is crucial since even a small layer can cause sudden boilover at higher burning rates. Managing water-fuel emulsions is also critical to avoid hidden pockets of water that can rapidly turn into steam. In terms of constructive measures, the use of thermal insulation helps slow down heat conduction to the tank's bottom, potentially extending the time before a boilover occurs. Adjusting tank geometry to include proper drainage and slopes can further reduce water retention, while advanced monitoring systems like real-time thermocouple arrays and mass-loss measurements are employed to predict the onset of a boilover.

A further innovative approach involves the integration of multisensory early warning systems linked to predictive algorithms. These systems combine real-time data from multiple indicators—such as temperature gradients, heat flux, and fuel mass loss—and use calibrated boilover models to trigger automated alerts or activate suppression systems. Such predictive frameworks enable dynamic adaptation of emergency protocols before critical thresholds are reached.

Another preventive strategy includes the implementation of fuel classification protocols based on boilover sensitivity. By categorizing stored liquids according to key physical and thermochemical properties - such as density, heat capacity, boiling point, and water solubility - fire safety engineers can assign specific intervention procedures tailored to each fuel type. This enhances decision-making and response planning, particularly in facilities storing mixed classes of combustible liquids [17].

Additionally, dual drainage systems with automatic thermal activation represent a highly effective structural safeguard. These systems are designed to automatically open secondary drainage channels if the tank bottom temperature exceeds predefined safety thresholds. By rapidly evacuating accumulated water before it reaches a critical evaporation point, this measure helps to prevent boilover in scenarios where manual intervention might be delayed or impossible [8].

Organizational measures are also integral to prevention, with regular personnel training focusing on critical roles such as managing the rate of mass loss and water accumulation. Maintenance and inspection routines ensure that drainage systems, seals, and measurement devices are

functioning properly, enhancing overall safety and preparedness.

Response strategies are varied and cater to different emergency scenarios. Foam application is a primary response, reducing oxygen availability and cooling the surface layer, with continuous monitoring required to maintain effective coverage, especially with volatile fuels. Cooling techniques include external water sprays on tank walls to limit downward heat transfer and, more rarely, internal cooling, which carries the risk of water entrapment beneath the hot fuel. Controlled fuel removal strategies, such as lowering the fuel depth, can delay boilover by shortening the heat path, although this requires specific infrastructure and adherence to safety protocols due to the risks involved with transferring hot fuel. Smoke and gas management are critical, as high mass burning rates ( $\dot{m}$ ) can produce large quantities of hazardous combustion products, with ventilation strategies often being limited but potentially supplemented by external cooling and foam. Lastly, effective communication and coordination through an operational center that receives real-time data on  $\dot{m}$  and temperature are essential, deciding on the appropriate response measures like foam application or cooling. Evacuation protocols are established to act preemptively if  $\dot{m}$  exceeds critical thresholds, ensuring safety and minimizing risk to personnel and infrastructure.

The implementation of the strategies highlights the need for a structured prioritization of prevention and response measures based on their influence on fire dynamics. The following Table 1 categorizes each measure according to its criticality and effectiveness in controlling the two key parameters: time to boilover and mass burning rate. This prioritization framework supports decision-makers in optimizing fire safety protocols by focusing on the most impactful interventions.

TABLE 1: PREVENTION AND RESPONSE MEASURES

Measure	Priority Level	Justification/Influence
Real-time thermal monitoring systems	Critical	Enables early detection of approaching boilover through heat gradient tracking.
Predictive alarm systems with multisensory inputs	Critical	Combines thermal, mass loss, and flux data with AI models for early intervention triggers.
Water drainage management	Critical	Eliminates the root cause of boilover by removing water accumulation.
Dual drainage systems with automatic	Critical	Ensures passive drainage during emergencies, reducing reliance

Measure	Priority Level	Justification/ Influence
thermal activation		on human response.
Automated foam application systems	High Importance	Shortens response time and reduces heat flux; especially critical during high $\dot{m}$ .
Tank cooling systems (external sprays)	High Importance	Limits vertical heat transfer and slows heat wave propagation.
Dynamic firefighting strategies based on mass burning rate ( $\dot{m}$ )	High Importance	Allows scalable foam and cooling tactics according to real-time combustion intensity.
Fuel removal infrastructure for emergency depth reduction	High Importance	Reduces fuel column, delaying heat transmission to the water layer.
Fuel classification protocols based on boilover sensitivity	High Importance	Enables tailored intervention strategies for different liquid fuels based on thermophysical properties.
Floating thermal shields	Supplementary	Reduces surface heat absorption and delays internal heating, but adds operational complexity.
Segmented tank design	Supplementary	Contains spread of burning liquid during partial boilover, applicable to new constructions only.
Drone-based thermographic monitoring	Supplementary	Enhances situational awareness but serves primarily as an auxiliary measure.
Multimodal prediction approach	Supplementary	Improves forecast accuracy but requires high computational input and calibration.
Differentiated evacuation thresholds based on $\dot{m}$	High Importance	Facilitates proactive protection of personnel based on measurable

Measure	Priority Level	Justification/ Influence
		hazard escalation.
Regular emergency drills for boilover scenarios	High Importance	Builds preparedness and improves coordination under real fire conditions.

#### IV. CONCLUSION

In addressing the critical challenges associated with petroleum product storage tank fires, particularly the hazardous phenomenon of boilover, this study highlights the necessity of integrating precise experimental data and robust theoretical frameworks into practical fire safety strategies. The findings underscore the complex relationship between key parameters specifically, the time to boilover and mass burning rate and their implications for effective fire prevention and response.

Experimental results demonstrate significant discrepancies between theoretical predictions and observed outcomes, reinforcing the importance of accounting for fuel-specific properties, environmental conditions, and tank design features in risk assessment models. The variation observed among different fuels emphasizes the need for tailored safety protocols and adaptive intervention strategies, particularly in scenarios involving fuels with distinct thermophysical characteristics, such as diesel and motor oils.

The study identifies critical preventive measures, including effective drainage systems, thermal insulation, and advanced monitoring technologies, which collectively enhance safety by delaying or preventing boilover events. Additionally, dynamic response tactics—such as adaptive foam application, external cooling, and real-time data monitoring—are shown to significantly reduce risks when promptly and appropriately implemented.

Ultimately, this research contributes valuable insights toward the development of comprehensive, predictive, and adaptable fire safety management practices. Continuous validation and refinement of these strategies against experimental data are recommended to ensure their reliability and effectiveness in diverse operational conditions. These steps will significantly strengthen the capacity to safeguard human life, infrastructure integrity, and environmental sustainability in the face of petroleum product storage tank fires.

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