

# *A study of the Boilover Phenomenon. Experimental Determination of Mass Burning Rate and Boilover Time*

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**Abstract-** The phenomenon of “boilover” a catastrophic event characterized by the explosive ejection of burning liquid from heated storage tanks, poses significant safety risks in industrial settings. This study investigates the critical parameters influencing boilover, such as mass burning rate and time to onset, utilizing a meticulously designed experimental apparatus that simulates real-world conditions on a reduced scale. The experiment setup includes a combustion chamber, precise thermocouple arrays for temperature monitoring, and scaled-down oil storage models to replicate the thermal dynamics observed in actual tanks. By observing the combustion process from its initiation to the critical boilover event, this study not only tracks the progressive temperature changes but also identifies specific precursor signals of impending danger. The research employs a combination of direct observation and sophisticated data analysis techniques to dissect the interactions between the burning fuel and the underlying water layer, crucial for understanding the boilover mechanism. Enhanced by mathematical modeling, the findings propose predictive tools that forecast the timing of boilover, enabling preemptive safety measures. Ultimately, this study aims to refine risk assessment practices and improve preventive strategies, thereby safeguarding lives and property against one of the most dramatic threats in fire safety management when handling and storing flammable liquids.

**Keywords-** *boilover, experiment, mass burning rate, time to boilover.*

## I. INTRODUCTION

The occurrence of “boilover” in storage tanks presents significant safety risks within industries handling flammable and combustible liquids, characterized by a sudden, violent ejection of burning fuel from heated storage vessels. This event drastically escalates fire intensity, threatening infrastructure integrity, environmental safety,

and posing extreme hazards to emergency responders, including firefighters engaged in suppression and rescue operations [1], [2], [3].

Historical incidents, laboratory experiments, and theoretical analyses underscore the critical necessity of comprehensive research into boilover phenomena to enhance preventive strategies and improve emergency responses.

Boilover typically occurs during fires involving storage tanks containing oils, petroleum products, alternative fuels, or vegetable oils layered atop water, which may accumulate due to condensation, leakage, or firefighting activities. The mechanism involves complex thermal and physical interactions, notably heat transfer from the burning fuel to an underlying water sublayer, creating conditions for explosive vaporization and ejection of fuel [4]. The boilover process occurs in distinct stages, including the steady burning stage, “slop over,” “froth over,” and the violent “boilover” itself. During steady burning, a hot layer forms and gradually propagates downward into the fuel layer. “Slop over” describes discontinuous frothing releases of fuel, generally from one side of the tank, while “froth over” represents a continuous, less intense release akin to rolling liquid. Finally, “boilover” constitutes the most violent and hazardous stage, characterized by explosive fuel ejection and fireball formation [5].

Several researchers have provided critical insights into these mechanisms. [6] investigated steady-state combustion dynamics of oil slicks on water, establishing foundational thermal transfer relationships widely referenced in boilover studies [7].

In-depth analyses furthered understanding through models predicting boilover onset based on experimental data, emphasizing thermal interactions between fuel layers

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and water substrates [2]. This paper highlighted specific combustion characteristics of crude oil, detailing the precursors and conditions necessary for boilover occurrence through extensive experimental validation of [3].

Fundamental insights into liquid fuel combustion dynamics and diffusion burning characteristics essential to boilover studies were pioneered by [3], [8] who provided critical empirical data and theoretical models still widely utilized today. The complexities involved in heat propagation through layered liquids, especially heat accumulation in water sublayers, were rigorously addressed through mathematical models employing inverse Stefan problems, greatly enhancing predictive accuracy [9].

Further, [4] provided comprehensive theoretical frameworks on fire dynamics, crucial for conceptualizing boilover phenomena within broader fire safety contexts. [10] complemented this theoretical knowledge by advocating detailed experimental modeling to validate predictive theories effectively, bridging gaps between empirical data and theoretical predictions.

Despite significant advancements, systematic validation of boilover predictive models remains limited, particularly regarding diverse fuel properties and mass burning rate influences. This study aims to address these gaps by systematically quantifying key parameters, such as mass burning rate, temperature gradients, and boilover onset timings under controlled experimental conditions. Ultimately, this research seeks to refine predictive models, enhancing industrial safety protocols and emergency response strategies, significantly mitigating the catastrophic impact of boilover incidents.

## II. MATERIALS AND METHODS

The prediction of the time required for the onset of the "boilover" phenomenon in a burning tank containing oil, petroleum products, alternative fuels, and vegetable oils is of utmost importance. This allows firefighters on the scene to be alerted, enabling the timely evacuation of all individuals near the fire. Accurate prediction of the phenomenon's onset time necessitates information about the type and quantity of the stored substance, as well as the presence of water in the tank.

To develop a model for predicting the boilover onset time, it is essential to study the formation and growth of the hot layer. Subsequently, an accurate profile of the heat transfer rate between the hot layer and the underlying fuel must be established, along with the heat transfer from the heated tank walls to the fuel layers beneath the burning one.

Research shows that boilover occurs within seconds after the water layer within the fuel reaches a temperature of 100°C. Therefore, a precise analysis of the temperature interface between the water and fuel layers is a viable method for predicting the phenomenon.

Due to the large size of fuel tanks, heat transfer within them is significant. Consequently, cooling the tank walls

has little influence on the formation of the hot layer and, therefore, on the occurrence of boilover.

### Materials Used:

- *Combustion Chamber:* A controlled environment where the burning experiments are conducted. This chamber is designed to safely contain the fire and prevent external influences;
- *Oil Storage Tank Models:* Scaled-down versions of real oil storage tanks, typically made from metal, used to simulate real-world scenarios. These models are filled with oil and a layer of water to mimic the conditions found in industrial storage tanks;
- *Thermocouples:* Used to measure temperatures at various points within the tank. These are essential for monitoring the progression of heat through the layers of oil and water.

### Methods employed:

- *Experimental Setup:* The experiment involves setting up the scaled-down tank models within the combustion chamber. These tanks are filled with a predetermined ratio of oil and water;
- *Data Collection:* Temperature data collected from the thermocouples are logged continuously through a data acquisition system. This data is crucial for mapping the temperature gradient and for modeling the conditions leading to boilover;
- *Data Analysis:* The collected data (temperature and oil level reading) are analyzed to identify the key thermal dynamics and physical behaviors that precede a boilover event. This analysis helps in refining predictive models for boilover.

The expulsion refers to the spilling of the tank's contents over its entire external surface. The spreading of burning fuel poses significant risks to the environment, equipment, and human safety. In the study [9] reported the formation of a hot zone within the fuel layer (crude oil and kerosene) during the combustion process. The mechanism behind the formation of such a hot zone in the fuel layer examines the process of distillation of fuel components and the heat transfer toward the water sublayer and the tank walls.

Both models are developed in the study of [10]. The reason for selecting lies in their ability to incorporate variable values derived from the experimental setups.

$$t_b = -20.5235 + 557.2043 \frac{H_0}{\sqrt{D}} \quad (1)$$

$t_b$  = Time to boilover occurrence (min).

$H_0$  = Initial thickness of the fuel layer (m).

$D$  = Diameter of the tank (m).

This model assumes that the time to boilover is influenced by the initial thickness of the fuel layer and the diameter of the tank. It suggests a linear relationship with these variables.

$$t_b = \frac{H_0}{V_{hz}} - k(H_0 + H_w) \quad (2)$$

$t_b$  = Time to boilover occurrence (min).  
 $V_{hz}$  = Growth rate of the hot zone (m/min).  
 $H_0$  = Initial thickness of the fuel layer (m).  
 $H_w$  = Thickness of the water layer (m).  
 $k$  = Coefficient, where  $k=0$  if the fuel temperature is below its ignition temperature, and  $k=1$  otherwise.

$$V_{hz} = \frac{\Delta h}{\Delta \tau} \quad (3)$$

$\Delta h$  = distance between the first and the third thermocouple (m).  
 $\Delta \tau$  = The time between thermocouple three reaching 100 °C and thermocouple one reaching 100 °C (min).

This correlation accounts for the growth rate of the hot zone, the initial thickness of the fuel layer, and the thickness of the water layer beneath the fuel. It also introduces a coefficient that varies depending on whether the fuel temperature is below its ignition temperature.

### III. RESULTS AND DISCUSSION

During the experimental study of the boilover phenomenon, six experiments were conducted using flammable liquids (diesel fuel, motor oil and sunflower oil) with varying amounts of fuel added to the system. In the initial experiments, the boilover effect was not observed, which can be attributed to insufficient time for the development of a "hot layer" beneath the fuel surface. Additionally, the distillation of the fuel occurred rapidly, predominantly yielding heavier distillates that did not sustain burning effectively.



Fig. 2. Extinguishment due to the insufficient amount of fuel.

As the experiments progressed, more fuel was added to the crucible, increasing the energy within the system. This adjustment facilitated the development of the "hot layer" essential for the onset of boilover. This layer acts as a thermal reservoir, gradually heating the underlying non-flammable layer (typically water), leading to the eventual boilover effect. During the experiments the "boilover" phenomenon was observed with the presence of all its stages.



Fig. 2. Stages of boilover occurrence.

The results from the six experiments and the correlations employed are shown in Table 1. Each experiment investigated variables such as fuel layer thickness, heat wave propagation and the dynamics of temperature distribution leading to „boilover”.

TABLE 1 STUDY RESULTS

No	Fuel	Experimental time to boilover	Correlation 1 (min)	Correlation 2 (min)	Heat wave propagation (m/min)	Mass burning rate $\dot{m}$ (g/m <sup>2</sup> s)	Temperature of boilover occurrence
1.	Diesel fuel	*	*	*	*		*
2.	Diesel fuel	*	*	*	*		*
3.	Diesel fuel	16,3	12,68	8,8	0,005 13	0,014	107,6
4.	Motor oil	19,1	17,42	14,29	0,003 36	0,050	172,9 **
5.	Motor oil	21,2	22,17	19,76	0,003 30	0,284	103,9
6.	Non refined sunflower oil	24,5	26,91	2,06 **	0,018 5	*	*

“\*” – No data

“\*\*” – Large deviation

The results provided critical insights into the mechanisms and predictive models for determining the onset of this phenomenon. Observations confirmed the importance of precise measurements of thermal transfer, which were analyzed using both manual data collection and computational tools like the "Polymonitor" program.

Experiment one was terminated due to an incorrect connection of the thermocouples. Experiment two showed that the “boilover” phenomenon does not occur when the fuel quantity is insufficient, confirming the necessity for a sufficiently energetic "hot layer." Experiments three and four, involving diesel fuel and motor oil, demonstrated violent boilover events, with the presence of all its stages, consistent with previously reported experimental analyses of fuel burning on water layers [10], characterized by sharp temperature rises (107.6 °C and 172.9 °C respectively), as illustrated in Figure 3.



Fig. 3. Boilover phenomenon

These findings show a strong correlation between the mass burning rate and the intensity of the boilover – motor oil displayed significantly higher burning rates (0.050–0.284 g/m<sup>2</sup>s), which explains the severity of the event.

In experiment five, the excessive fuel volume led to flame smothering during the frothing phase. Experiment six showed a boilover without ignition, highlighting the low flammability of unrefined sunflower oil despite considerable heat accumulation.

Analysis of numerical values from Table 1 indicates that the applied predictive correlations (equations 1 and 2) yielded results closely matching experimental values, particularly in experiments 3-5. Significant deviations, especially with sunflower oil, suggest the need for model adaptation based on the specific physicochemical properties of fuels. The propagation speed of the heat wave (ranging from 0.0033 to 0.0185 m/min) also significantly influenced water layer evaporation dynamics and time to boilover.

#### IV. CONCLUSIONS

This research focuses on the experimental and theoretical investigation of the "boilover" phenomenon during the combustion of flammable liquids stored above water layers, including diesel fuel, motor oil, and unrefined sunflower oil. The phenomenon, characterized by the sudden and explosive ejection of burning liquid, poses significant fire safety hazards in industrial facilities handling hydrocarbons, alternative fuels, and vegetable oils.

A specially designed experimental setup was developed and validated to simulate real-world storage conditions at a reduced scale. Experiments measured critical parameters such as mass burning rate, heat wave propagation speed, and the time to boilover onset. Data were analyzed using two correlation models and compared against experimental results to assess model accuracy.

Key findings indicated that:

- The mass burning rate and heat wave propagation speed are the primary predictors of boilover onset.
- Higher mass burning rates, particularly observed with motor oil, led to more intense and violent boilover events.
- Fuel properties, such as flammability and thermal behavior, significantly influence the accuracy of predictive models.
- While the models showed good predictive capability for diesel and motor oil, significant deviations were found for unrefined sunflower oil, highlighting the need for model adaptation based on specific fuel characteristics.

Future work will extend the research by scaling the experimental apparatus to larger vessel diameters (up to 150 cm) and studying the impact of turbulent flame regimes on boilover formation. The ultimate goal is to refine risk assessment methodologies and enhance preventive strategies for facilities that store and process flammable liquids.

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