A Small-Scale Study on the Time Taken For Burning Fuel to Boilover

by

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ABSTRACT

This study is about the boilover process that happens in tanks containing fuels like crude oil. The boilover process can take place during a fire in an open tank containing crude oil or other types of fuel consisting of a wide range of boiling points. Oil products are flammable and possess a threat for tank fires to occur. When crude oil burns, there is a potential of frothing or boilover to happen where the volume of the expelled product is many times that of the oil in the tank. The burning oil may flow over and set adjoining tanks on fire and may destroy anything in its path. Burning fuel form descending heat waves that progresses downward and upon reaching the bottom of the tank, as it comes in contact with the layer of water or water-in-oil emulsion, it gives a rise to an explosive vaporization of the water. This is usually referred to as boilover by “hot zone formation”, a zone of practically uniform temperature and composition that propagates through the interior of the fuel.

The investigation of the boilover process have been mostly based on large-scale experiments and thus the analysis made has to incorporate many conditions and variables and this further complicates the study and it makes it harder to control the experiment. In addition to that, the risks and cost involved in fabricating a boilover at a large scale are very high. Therefore, for the purpose of this study, the experiment was performed in a smaller scale to enable better facilitation of the experiment and to determine the feasibility of the study on a small scale. From the experiments it was deduced that the time to boilover increased as the thickness of the fuel layer increased, forming a linear relationship. It was concluded that a small scale boilover study is appropriate to study the mechanism and the characteristic of the phenomenon however; it is not the best option when accuracy of the values are crucial.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

The production of crude oil has been increasing over the years due to its high global demand and this has propped the rise of large quantity of oil storage facilities. Storage of this amount of fuel can pose great safety management concerns due to the risk of a catastrophic fire hazard. Despite the fact that the petroleum and chemical industry is continuing to mature and with it, the increase in demand for better design, construction, standards and fire protection the industry still fails to prevent this catastrophes from happening. In view of the past 50 years or so, around 480 major tank fire incidents were reported and 3% of that recording is due to boilover (Chang & Lin, 2006). The percentage may look small compared to other causes and it might seem to pose very little threat. However, there are some factors that determine the scale of hazard and they are the (Lees, 2001):

i. inventory
ii. energy factor
iii. time factor
iv. intensity- distance relations
v. exposure factor
vi. intensity-damage and intensity- injury relationships.

Therefore, weighing on these factors and judging by the nature of a boilover process, the failure to prevent one from happening, can have enormous significant effects that would result in the loss of lives, damage of property and even to the environment thus regarding it as a major hazard, regardless of the frequency of its occurrence.

1.2 Boilover

The National Fire Protection Association (NFPA) defines boilover as “an event in the burning of certain oils in an open-top tank when, after a long period of quiescent burning, there is a sudden increase in fire intensity associated with expulsion of burning oil from the tank. Boil-over occurs when the residues from surface burning become more dense than the unburned oil and sink below the surface to form a hot layer, which progresses downward much faster than the regression of the liquid surface. When this hot layer, called a "heat wave," reaches water or water-in-oil emulsion in the bottom of the tank, the water is first superheated and then boils almost explosively, overflowing the tank. Oils subject to boil-over consist of components having a wide range of boiling points, including both light ends and viscous residues. These characteristics are present in most crude oils and can be produced in synthetic mixtures” (NFPA 30 , 2000).

The boilover by ‘hot zone formation’ is where a zone of practically uniform temperature and composition propagates through the interior of the fuel. The conditions for this boilover to occur (1) the presence of water, (2) the formation of a heat wave and lastly, (3) fuel is viscous in nature.

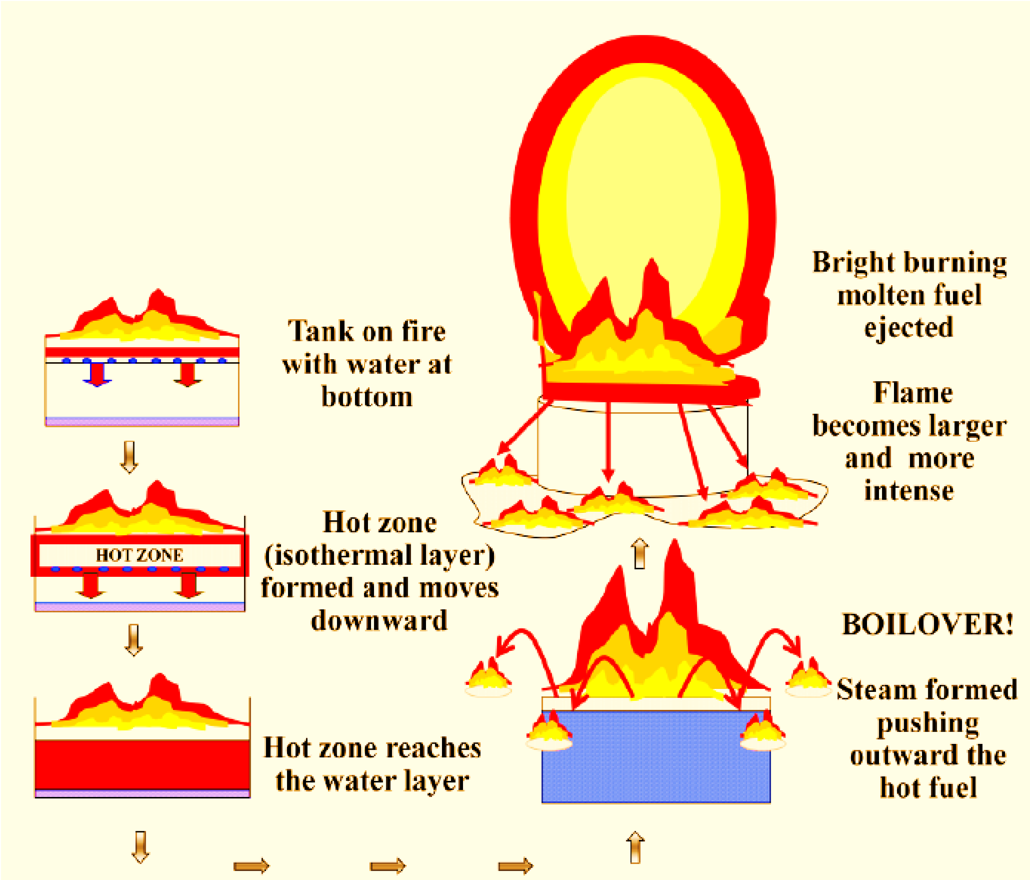


Figure 1: Mechanism of the boilover process

There are basically three types of fuel ejection from the tank can be identified in three forms as shown in Figure 2 (Broeckmann & Schecker, 1995):

i. *Frothover* where there is a steady, slow intensity fuel release that usually occurs during the tank filling when hot dense material is put into a tank that sinks and vaporises the sub layer causing the tank to overflow.

ii. *Slopover* occurs when water is applied to the already burning surface of the tank fire and discontinuous frothing release of fuel from the tank on one side of its wall occurs. The water sinks into the heavier oil at the surface of the tank and vaporises.

iii. *Boilover* is the most violent form where it is similar to the frothover but with a huge increase in burning rate and can send a column of flame high into the air resulting in fire enlargement and formation of fireballs and a frothing over of the entire tank content.

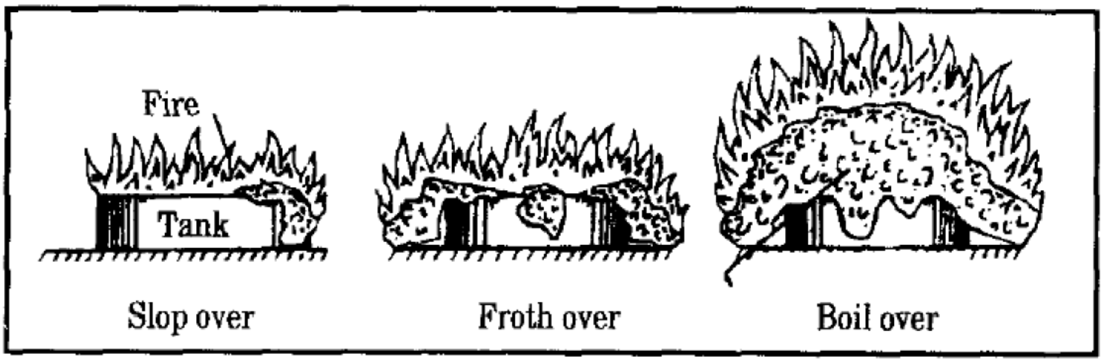


Figure 2: Different types of fuel ejection.

There is still much to be understood of the boilover phenomenon and at present many researches are dedicating their interest to form a fundamental point of view, especially its mechanism and the theoretical prediction of the critical condition of its onset. Greater understanding of the mechanism is crucial as boilover implies an enormous danger to the surroundings, equipment and humans. Therefore, this study aspires to contribute to this field of research in hopes that a wider conception and appreciation of the boilover process can be attained.

1.3 Problem Statement

The impact of a boilover is extremely detrimental and would result in great amount of losses. The first step to ensure preventive measures or damage control actions can transpire is to have a good understanding of the phenomenon. The major efforts done to investigate the boilover process have been based on large-scale experiments. In doing so, the analysis done has to incorporate many conditions and variables to justify the experiment as on a large scale, many factors should be noted and quantified. This scenario may further complicate the study on the time taken for burning fuel to boillover and it makes it harder to control the experiment. Also, the risks and cost involved in fabricating a boilover at a large scale are very high. Therefore, experiments at a smaller scale would reduce the risks involved, the cost and also to enable better facilitation of the experiment.

1.4 Objectives

i. To determine the feasibility of the study on a small scale.

ii. To observe effect of different proportions of fuel used on the occurrence of boilover.

iii. To determine the time taken for the boilover process by varying the thickness of the fuel layer.

iv. To develop a correlation between the fuel layer thickness and the time to boilover.

1.5 Scope of Study

This study focuses on the parameters of the fire subsystem: the thickness of the fuel layer and other conditions that predefine the boilover process like the time for boilover to start and the type and proportion of fuel used. This experiment only considers the fuel layer only and none of the heat transfer effect of the water sub layer is accounted for.

CHAPTER 2

LITERATURE REVIEW

The study on the boilover mechanism has been of significant interest to fire safety science considering the huge amount of risk it represents. Therefore, a number of theoretical and experimental studies have been conducted and published concerning this topic. These initiatives have been undertaken in order to promote better understanding of the heat transfer mechanism and all the other parameters that come to play in a boilover process. This chapter covers some of the literatures that have studied and reviewed the boilover process to allow a better understanding and to technically evaluate the theory and relevant findings prior to experimental boilover studies.

2.1 Basic Principles

In an attempt towards understanding the boilover phenomenon, one of the pioneer researchers of the boilover process, Hall, a Chief Engineer of the Standard Oil Company of California in 1925 performed an experimental research where around 100 tests were carried out. His study later further encouraged more researchers to study the formation mechanism of the hot zone in the oil layer by considering the effects of multiple components of oil and heat conduction by the oil tank wall.

One of the most important findings which later inspired more researches was the identification of three physical conditions necessary for a boilover to take place. These conditions are: (1) the presence of water, (2) the occurrence of heat wave, and

(3) significantly viscous content. The hypothesis adopted by Hall (1925) on the workings of the boilover process, coincides with the definition by the National Fire Protection Association (NFPA) with one additional detail. As opposed to Hall's indistinct mentioning of the boiling process, the NFPA-30 clearly states that the water is superheated and then boils which proposes that the water layer at the bottom of the bottom of the tank must exceed the atmospheric boiling temperature of water at 100°C.

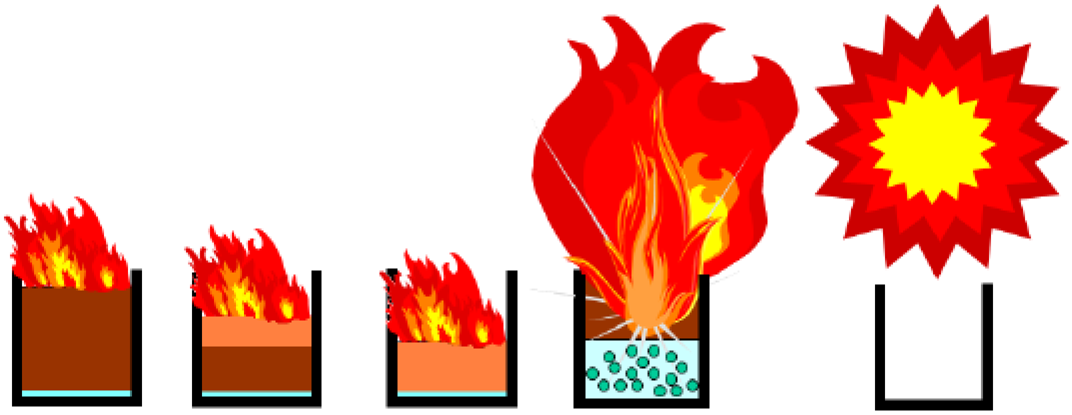


Figure 3: Boilover principle. *Retrieved from* (Laboureur, 2012)

The rationale of the first condition by Hall is that the energy generated from the conversion of water to steam is what forces the fuel to expel from the tank. In fact, the reason why boilovers react so violently is because when the heat zone comes in contact with the water, it is superheated and expands to a water-to-steam expansion ratio of 1700:1. Therefore, even small amounts of water can produce large volume of steam (Dornon, 2005).

Naturally, water is present in oil reservoirs in a separate layer at the bottom of the tank. However, sometimes due to process needs, water can also be found in the crude oil content in the emulsified form and the percentage of the water in the tank varies with the oil source. The presence water at the bottom of the tank increases the likelihood for a boilover to happen.

However, (Hall, 1925) states that increasing the thickness of the water layer at the bottom of the tank does not guarantee that boilover will in fact occur.

The second condition is for the presence of a heat wave or hot zone formation. The hot-zone has an expansion rate higher than the burning rate of the fuel surface and this therefore enhances the heat propagation downwards to the water layer at the bottom of the tank (Hasegawa, 1989). This can only happen only if the fuel mixture has a wide range of boiling points and densities. Upon reaching the bottom of the tank, as it comes in contact with the layer of water, it gives a rise to an explosive vaporization of the water and boilover occurs.

Finally, the third condition is in relation to the viscosity of the oil. The crude oil or at least the residue at the bottom of the tank should be viscous in nature because once the heat reaches the water and converts it to steam, that steam must pass through a viscous medium to generate foam as it rises up to the oil above.

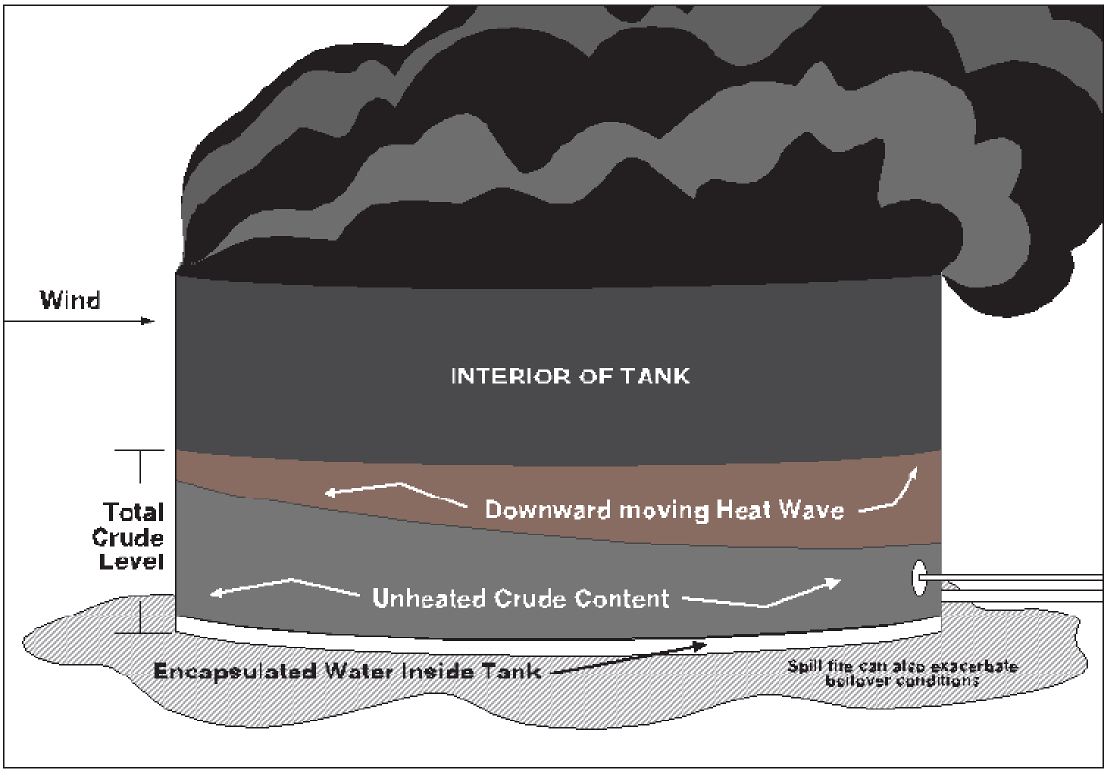


Figure 4: The make-up of a boilover process. ***Retrieved from*** **(Gaspard, 2012)**

In addition to the research by Hall, it was proposed that the boilover phenomenon can be divided in three different periods, from the ignition of the fuel surface to the end of the fuel burning after boilover and they are: the quasi-steady period, the premonitory period and the boilover period (Fan, Hua, & Liao, 1995).

i. **Quasi-steady period**: This period starts after the ignition of the fuel surface and a small initiation period where the flame propagates along the whole fuel surface. The fire burns in a regular way, with very few influence of the water sub-layer. The flame is stable and the flame size is constant with time.

ii. **Premonitory period**: The water layer temperature is quite close to the boiling point, and water bubbles develop at the fuel - water interface. They escape from the interface, pass through the fuel layer, and erupt from the fuel surface into the flame zone as oil-water dissolution droplets. The combustion of these oil-water bubbles emits a typical crackling sound.

iii. **Boilover period**: When the water vaporization is strong enough to push the fuel layer, prompting the boilover to starts. The burning fuel is sprayed out of the tank and the flame height increases significantly and quickly. The flame increase and the violent water vaporization also emit noise, with stronger amplitude than the micro-explosion noise.

Figure 3 shows the characteristics of the flame at each stage of boilover, using a 100 mm diameter oil tank model with an initial oil layer thickness of 50 mm. Photographs were taken (a) 5.0 min after ignition in the quasi-steady period, (b) 18.5 min and (c) 19.0 min after ignition in the premonitory period, and (d) 20.0 min after ignition in the boilover period.

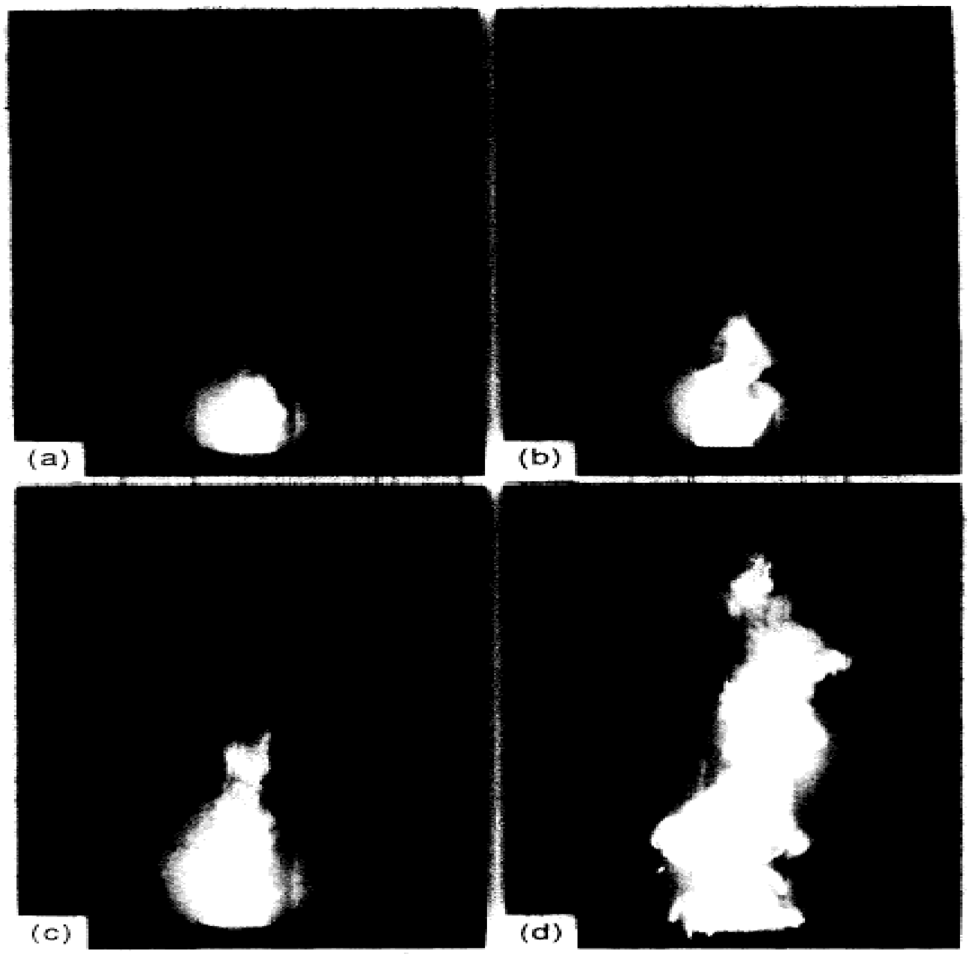


Figure 5: Typical characteristics of flames of crude oil burning on water.
Retrieved from (Fan, Hua, & Liao, 1995)

2.2 Hot-zone Formation

The simple explanation for the hot-zone formation is related to the distillation process where fuel components with different boiling points over a wide range create convection movements inside the fuel. The formation of hot-zones is the main difference between the typical and the thin-layer boilover.

Hall in his study explained that the hot-zone starts with a distillation process in a thin layer of fuel located just under the fuel surface. The heat then progresses and is transported by the heavy-ends of the hydrocarbon and vaporises the light-end fraction of the hydrocarbon.

As a continuation of the study by Hall, Burgoyne and Katan in 1947 conducted experiments using a small tank with the diameter of about 0.56m and another using a larger tank with the diameter of 2.74m. In their experiments, when crude and fuel oils burned, the lighter ends were removed layer by layer, leaving the hot residues or heavy ends to accumulate on the unaffected bulk oil. The thermocouple located at approximately 0.08m and 0.13m from the surface, showed readings of a similar temperature recording of 250°C at 50mins from the ignition time, thus indicating the presence of the hot-zone, accumulating and growing steadily under the surface.

However, unlike what was proposed by Hall, they suggested that at the hot/cold-unaffected zone interface, the hot ends were prevented from sinking deeper due to their lower density compared to the colder layer. They proposed a theory that the hot-zone is formed due to bulk circulation of the fluid. When the fuel burns, the light ends are vapourised at the hot/cold interface that supplies the fire and some heat energy is retained to allow the mass circulation of the Hot Zone Fluid. Once, the light end passes the hot/cold interface, it adds to the stirring effect of the mass circulation. The significance of this theory is that, rather than the mass transfer effects that were proposed by Hall, the temperature and composition of the hot zone are determined by the heat transfer coefficients at the hot/cold interface and the surface of the oil, inclusive of their thermal properties of the oil.

Blinov and Khudyakov in 1961 performed a study using small vessels that were heated externally through the wall. In doing so, boilover occurred and it was proposed that the growth of the hot zone could be propagated by conduction through the wall of the tank (Khudyakov & Blinov, 1961). This particular finding of theirs is different compared to the mechanism proposed by Hall and Burgoyne and Katan.

Hasegawa (1989) conducted tests using open top cylindrical tanks to burn gas oil, gasoline and the mixture of gas oil and gasoline. Following the test that were conducted, it was observed that no hot zone was formed in gas oil, but formed in the mixture of gas oil and gasoline. The mixture of 80% gas oil and 20% gasoline was used to observe the characteristics of the burning oil. The characteristics of the hot zone could be observed clearly and at the surface of the fuel, bubbles were seen bursting with the turbulence near the surface. Inside the hot zone, scattered vapour bubbles were observed where they rose quickly towards the surface and increasing in size due to the nucleation process. This ascent and growth of the bubbles resulted in the rising flow and sinking flow that contributed to the currents of continual and vigorous convection.

He concluded that the hot-zone, in addition to the uniform temperature, also has uniform density and chemical composition. It was also stated that for reservoirs with a diameter higher than 0.9 m, the hot-zone formation depends only on the fuel characteristics, as supported by the findings by Hall and Burgoyne. However, for reservoirs with diameter smaller than 0.3 m, the conduction through the wall of tank is the most important heat transfer, and that the heat exchange in the zone between the reservoir edge and the fuel surface contributes to the formation of the hot-zone. Lastly, for a reservoirs diameter between 0.3 m and 0.9 m, both the fuel characteristics and the surface temperature that is affected by the conduction with the tank wall, contributes to the formation of the hot-zone.

In 1994, following the research by Hasegawa, Koseki proposed that the uniformity of the hot-zone layer is due to the convection process and fuel vapour stirring as the layer propagates downwards. In addition to that, the temperature gradient at the hot/cold interface is due to the fact that heat is only being transferred by conduction considering that oil is a poor conductor of heat. He also concluded that the depth of the fuel was crucial to the time to boiilover and that the energy required to form the hot-zone layer is obtained mainly through radiation of heat from the flame as the heat from conduction through the tank wall is relatively small.

Apart from that, in 1995, Broeckmann and Schecker supported the findings by Koseki on the oscillatory nature of the hot-zone propagation. The temperature at the interface oscillates and it was proposed that this was due to the formation of vapour and the resulting convective puses that is the formation of bubbles causing upwards and downwards motion causing the colder fuel to replace it.

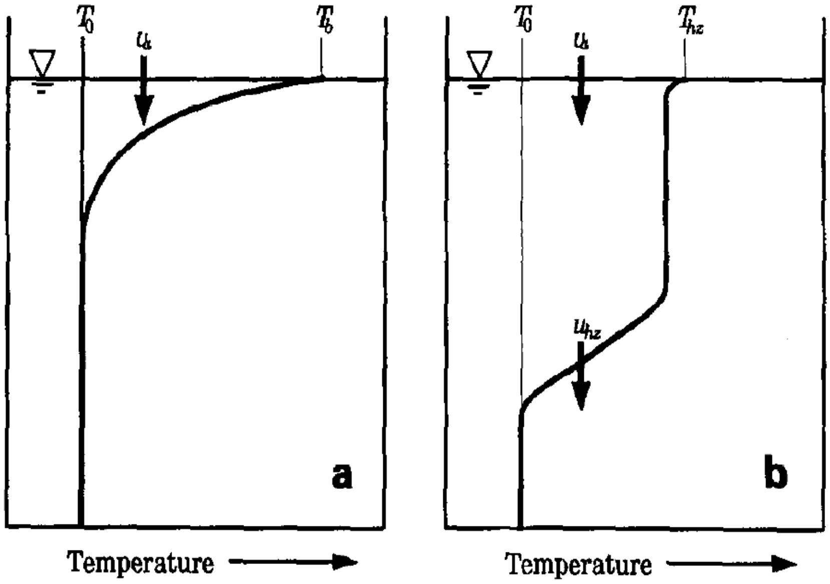


Figure 6: Temperature profiles in fuel. Left: without formation of a hot-zone, Right: with the presence of hot-zone. *Retrieved from*, (Broeckmann & Schecker, 1995).

2.3 Influence of Fuel Layer Thickness on Time Taken to Boilover

The common concept is that the boilover starts with the vapourisation of the water sub-layer that induces a piston effect due to the enormous volume increase from the phase change. In 1994, Koseki used different sizes of reservoir and different crude oil thickness to measure the time taken to boilover where hot-zone was observed. From these experiments he found that the time taken to boilover showed a linear progression with the fuel thickness, regardless of the diameter.

In an experiment by (Koseki, Kokkala, & Mulholland, 1991), it was reported that for studies conducted using pan with diameter of 0.3m to 1m, the maximum intensity of burning was found to be related to the hot zone thickness and to the initial fuel thickness. The intensity of the boilover was found to increase with increasing fuel thickness in a large-scale experimental study of boilover phenomena in connection with crude oil and kerosene pool fire. As a result of that, a hot zone of at least 5-10mm thickness was found necessary for boilover. Therefore, when trying to imitate boilover process in small scale experiments the minimum requirement of fuel thickness required for the phenomena to occur should be noted on.

In another study, to gain an understanding of the boilover phenomenon on a large scale, boilover experiments were conducted in a 1.9m diameter pan (Koseki, Natsume, Iwata, Takahashi, & Hirano, 2004). The experimental conditions are represented in the Table 1 below. It was concluded that the effects of the thicknesses of the fuel and the water layers were examined by comparing Runs #1–3. It is known that the time needed to reach boilover increased when the fuel layer thickness increased. Furthermore, fuel thickness is said to be an important factor to predict the onset of boilover, the time to boilover and its nature.

Table 1: Experimental Conditions

	Run #1	Run #2	Run #3	Run #4
Pan diameter (m)	1.9	1.9	1.9	4.0
Fuel thickness (mm)	100	200	400	400
Water thickness (mm)	700	500	300	0

In these experiments, it was found that the time needed to start boilover increased when fuel thickness increased. Also, the study pointed out that as long as the thickness of the water layer was sufficient, about 10mm or more, the fuel layer thickness would take precedence as the important factor to analyse. This is said to be due to the fact that the water layer essentially acted as a form of heat sink.

In 2006, a large-scale boilover experimental study was conducted using crude oil. Pan measuring the size of 5m diameter was used with the initial fuel layer of 0.45m and water layer thickness of 0.1m. The time recorded for the boilover to happen was 70mins. From the study, it was concluded that the maximum irradiance from the flame due to boilover was approximately 22 times more from steady burning and that the isothermal thermal growth rate and thickness as well as the temperature changed with time (Koseki, Natsume, Iwata, Takahashi, & Hirano, 2006). The summary of the experimental results are shown in figures below.

Run no.	1	2
Pan	$D = 5.0\,m$, $H = 0.9\,m$	$D = 5.0\,m$, $H = 0.9\,m$
Burnt oil (net amount)	2.4 kl (= 24% of initial fuel, = 119 mm)	2.5 kl (= 25% of initial fuel, = 122 mm)
Depth and temperature of isothermal layer when boilover occurred	331 mm, 282 °C	328 mm, 290 °C
Time to boilover (min)	78.8	66.4
Intensity of boilover[a]	5.8[b] 22.0[c]	4.6[b] 22.7[c]
Fuel level regression rate (average, mm/min)*	1.6[d]	2.0[d]
Rate of the isothermal layer growth (average, mm/min)	5.7	6.7

Figure 7: Summary of experimental results

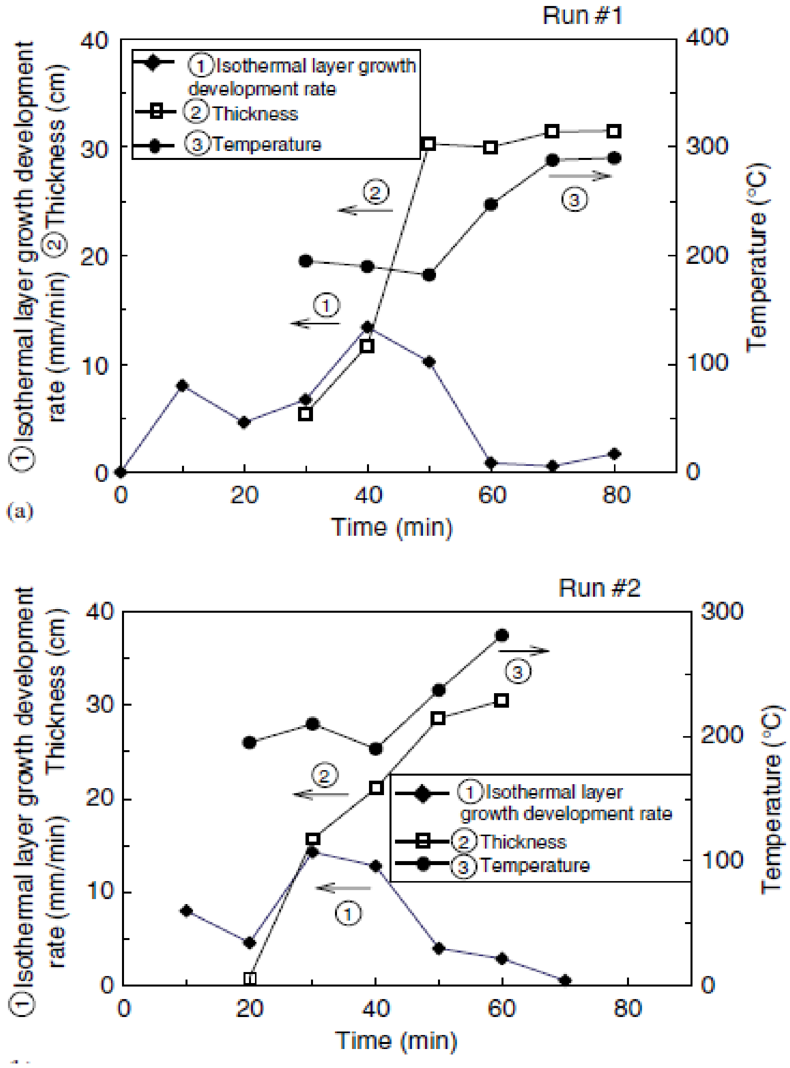


Figure 8: Time histories of isothermal layer growth rate, thickness and temperature of the isothermal layer

A recent study in 2012 by Laboureur showed consistent findings with previous studies mentioned earlier in the chapter. Figure 6 shows the boilover apparition time for a 0.08m diameter pan. From the graph it is evident that the influence of the fuel thickness on the time to boilover if linear.

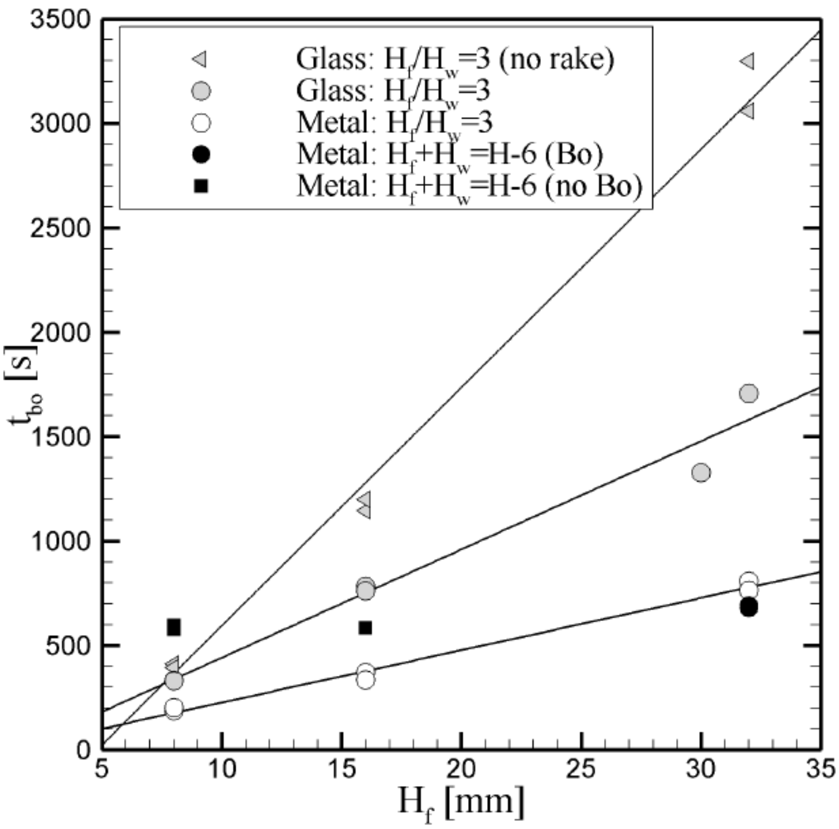


Figure 9: Boilover apparation time

CHAPTER 3

METHODOLOGY

The large scale tests conducted have further discussed and identified the processes involved in the hot zone formation including the growth and moving on to the occurrence of the boilover phenomenon. However, these large scale experiments are more complex and not to mention more costly to carry out. Therefore, it is more feasible to conduct the boilover study at a smaller scale as they would still behave similarly like the ones done on the larger scale. That being said, it is also one of the main objectives of this final year project study.

3.1 Experimental Site

The experiments conducted for this study are to be conducted outside the laboratory area. This experiment expects the occurrence of a boilover and due to the usage of flammable chemicals for safety purposes, the experiments should be conducted in an open field.

3.2 Apparatus

The burn boilover studies are to be conducted in an appropriate tin container size. In this study, a cylindrical tin container with a diameter of 19cm and a height of 7cm will be used as shown in Figure 8.

In addition to that, measuring cylinders will be used to measure the volume of the fuel used and stopwatches to record the time taken to boilover. A digital camera is also to be used to record and capture the experiment for later analysis.

3.3 Fuel Type

The proposed fuels to be used in the experiment are petrol, diesel, mixture of petrol and diesel and lastly crude oil. The mixture of petrol and diesel in to imitate the light-end and heavy-end components of fuel with a wide range of boiling points. Petrol being more volatile would act as the lighter key component when mixed with diesel.

3.4 Design of Experiment

The first part of the study would deal with the objective to determine the influence of the different proportions of fuel mixture on the time taken to boilover. The thickness of the fuel layer is to be kept constant and only the composition of the petrol and diesel will be varied.

The second part of the study is to determine the effect of the initial fuel layer thickness on the time taken to boilover. For the purpose of this experimental set-up, the composition of the fuel mixture will be kept constant. However, the initial fuel layer thickness will be increased from 2cm to 5 cm.Both parts of the experiment are to be repeated to obtain more accurate readings.

For the last part of the experimental procedure, crude oil is used as the fuel and the fuel thickness is varied again from 2cm to 5 cm to observe its effects on the time taken to boilover. It should be noted that the thickness of the water layer will be kept constant at 1cm throughout the whole experiment.

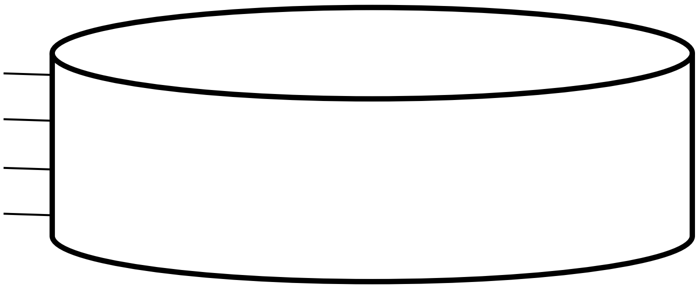


Figure 10: 19cm diameter pan labelled with 1cm indicators on the pan

3.4.1 Experimental Procedure

Preparation of the chemicals where the volume of the fuel is measured in a measuring cylinder

↓

The tin container is filled with water measuring up to 1cm

↓

The prepared and measured fuel is poured into container and is mixed to remove any bubbles

↓

The fuel is then ignited with a fire starter and time is recorded by starting the stopwatch

↓

Wait for the fuel to boilover and then record the time and until the fire extinguishes

↓

Let the residue to cool down before disposing it in the allocated container

3.4.2 Equations and Calculations

The thickness of the fuel layer is represented in centimeters. However, the measurement may not be as accurate and therefore its volume is calculated. The fuel is in liquid form and thus takes up the shape of the container which is cylindrical. Therefore, the following formula can be used:

$$Volume, V = \pi r^2 h \tag{1}$$

where,

π= constant with value approximately 3.142,

r= radius of the pan

h= height of fuel

<u>Example calculation for fuel layer = 2cm</u>

$V = \pi r^2 h$

$= (3.142)(9.5)^2 (2)$

$= 567 cm^3$

3.5 Key Milestones

There are several key milestones for this research project that must be achived in order to meet the objective of this project:

Problem Statement and Objective of the project

Developing and identifying the purpose of this research project

↓

Literature Review

Researching and gathering as much information as possible from various sources such as journals and websites gain more knowledge on the topic

↓

Experiment Design

Identifying the variables that needs to be investigated and the experimental procedures, as well as the chemicals required and the collection of results

↓

Data Analysis and Interpretation

The findings obtained are analyzed and interpreted critically. Comparison with other literature readings will also be done.

↓

Documentation and Reporting

The whole research project will be documented and reported in detail. Recommendations or aspects that can be further improved in the future will also be discussed.

3.6 Project Timeline

3.6.1 FYP 1

NO.	DETAILS / WEEK	January			February					March				April		
		1	2	3	4	5	6	7	MID- SEM BREAK	8	9	10	11	12	13	14
1	Selection of Project Topic	■	■													
2	Preliminary Reaserch Work and Literature Review		■	■	■	■										
3	Submission of Extended Proposal						●									
4	Proposal Defense presentation									■	■					
5	Project Work continues											■	■	■		
6	Submission of Interim Draft Report														●	
7	Submission of Interim Report															●

●	Suggested Milestones
■	Process

3.6.2 FYP 2

NO.	ACTIVITIES / WEEK	May		June				July						August			
		1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Experimental work and result analysis for project	■	■	■	■	■	■	■	MID-SEMESTER BREAK								
2	Submission of Progress Report									●							
3	Experimental work and result analysis for project									■	■	■	■	■			
4	Pre-SEDEX												●				
5	Submission of draft report													●			
6	Submission of Dissertation (soft bound)														●		
7	Submission of Technical Paper														●		
8	Oral presentation															●	
9	Submission of project dissertation (hard bound)																●

● Suggested Milestones

■ Process

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of fuel proportion on time to boilover

In order to study the effect of different proportions of fuel composition used, the composition of diesel and petrol was varied. The fuel thickness was kept constant at 3cm and the water level at 1cm throughout this part of the experiment. The experimental conditions are shown in Table 2.

Table 2: Experimental Conditions

Thickness of fuel layer, h_o (cm)	Volume (cm^3)	Fuel Type and Volume (cm^3)					
		70% Diesel	30% Petrol	60% Diesel	40% Petrol	50% Petrol	50% Diesel
3	851	596	256	511	340	425.5	425.5
Time taken to boilover (min)		17		16		18	

It was observed that no significant difference was demonstrated for the first part of the experiment as all the different composition of fuel used showed almost similar results where the time taken to boilover was approximately 18 minutes. However, it should be noted that for the fuel composition of 50% petrol and 50% diesel, the burning process was smoother and the boilover that happened was more evident. The burning process prior to the boilover at each stage is shown in Figure 9.

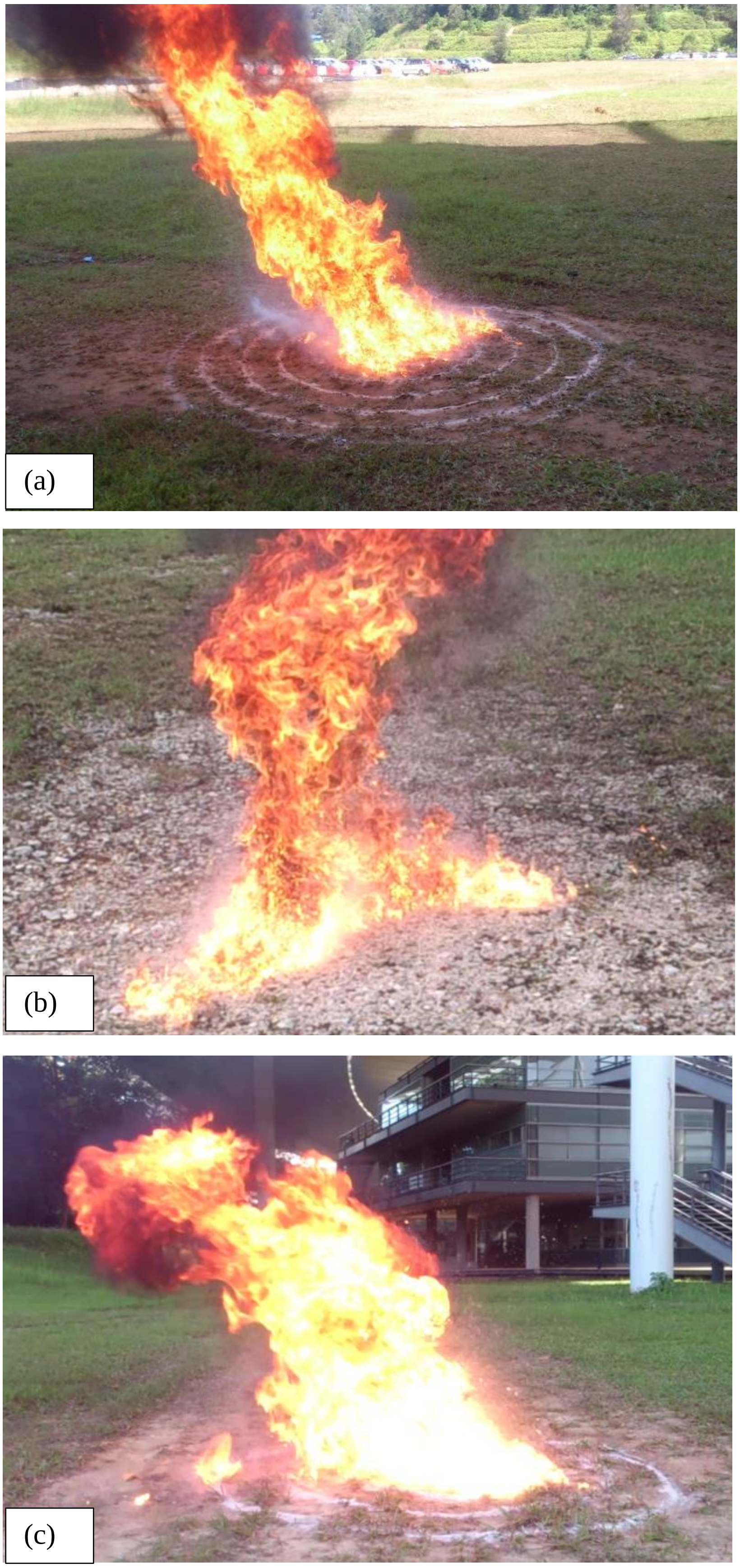


Figure 11: The boilover at different fuel composition. (a)70% Diesel-30% Petrol, (b) 60% Diesel-40% Petrol and (c) 50% Diesel-50% Petrol

Overall, the flow of the experiment is: in photograph (a), taken 3.0 min after ignition shows that the combustion is stable and since only the surface of the fuel is burning at this stage the combustion process during this period is no affected by the water layer at the bottom of the pan. Photographs (b), (c), and (d) was taken 5, 10 and 12 minutes respectively after ignition in the boilover. At around 15 minutes since the ignition, 'crackling' sound can be heard indicating that the heat is at the oil-water interface.

This period is additional to those of liquid pool fires without a water sub layer, and it also acts as a transitional combustion process from pool fires to boilover fires. Therefore, study of the physical process in this period may give us a more exact understanding of the mechanisms of boilover. At the 17 minutes mark, the sound appears to be getting louder and photograph (e), taken 18 min after ignition in the boilover period, shows the typical flame shape of boilover fires. The flame height increased quickly to the highest point and burning oil is sprayed out of the oil tank. Figure 11 shows the stages of the burning process before the boilover.

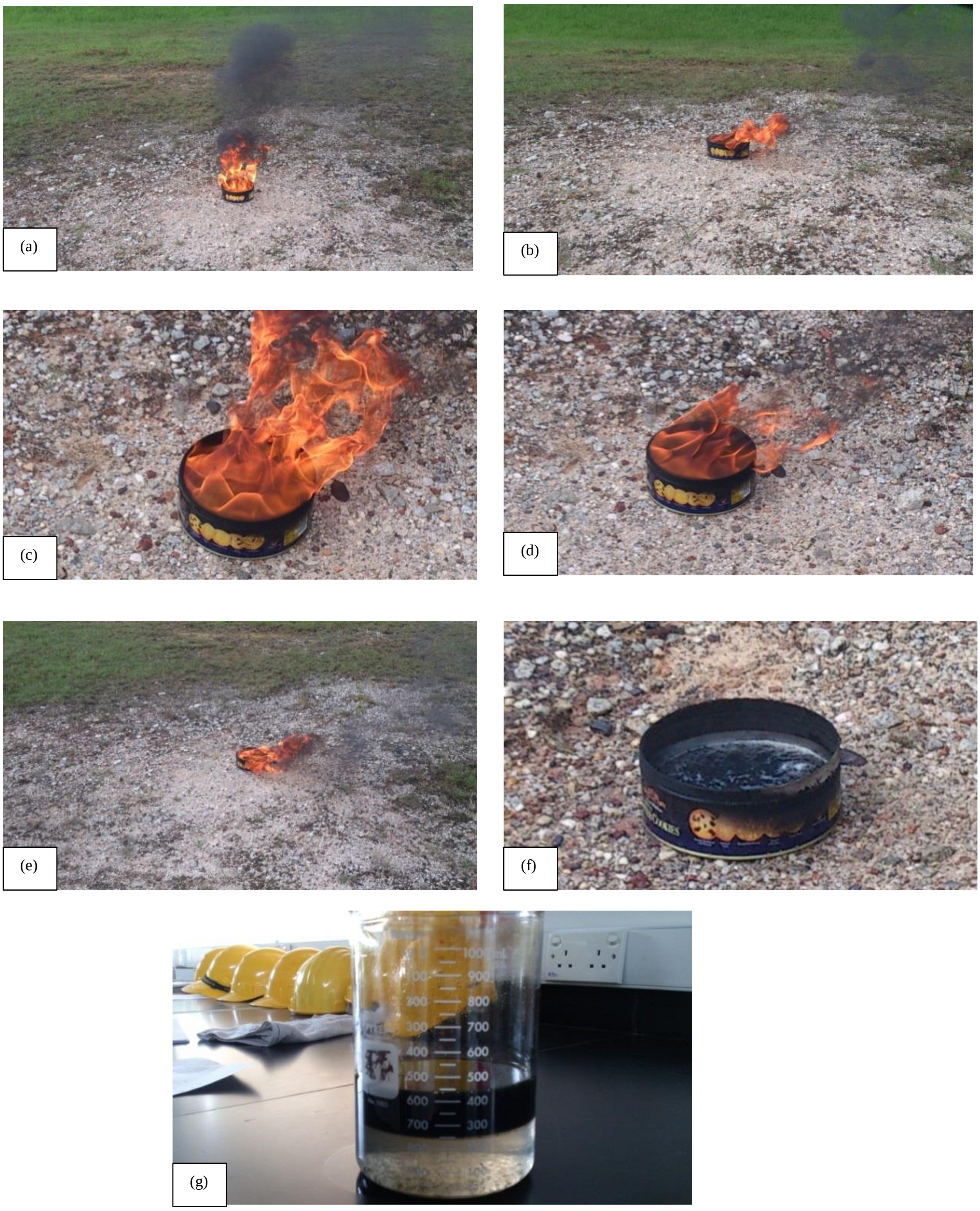


Figure 12: Burning stages prior to boilover

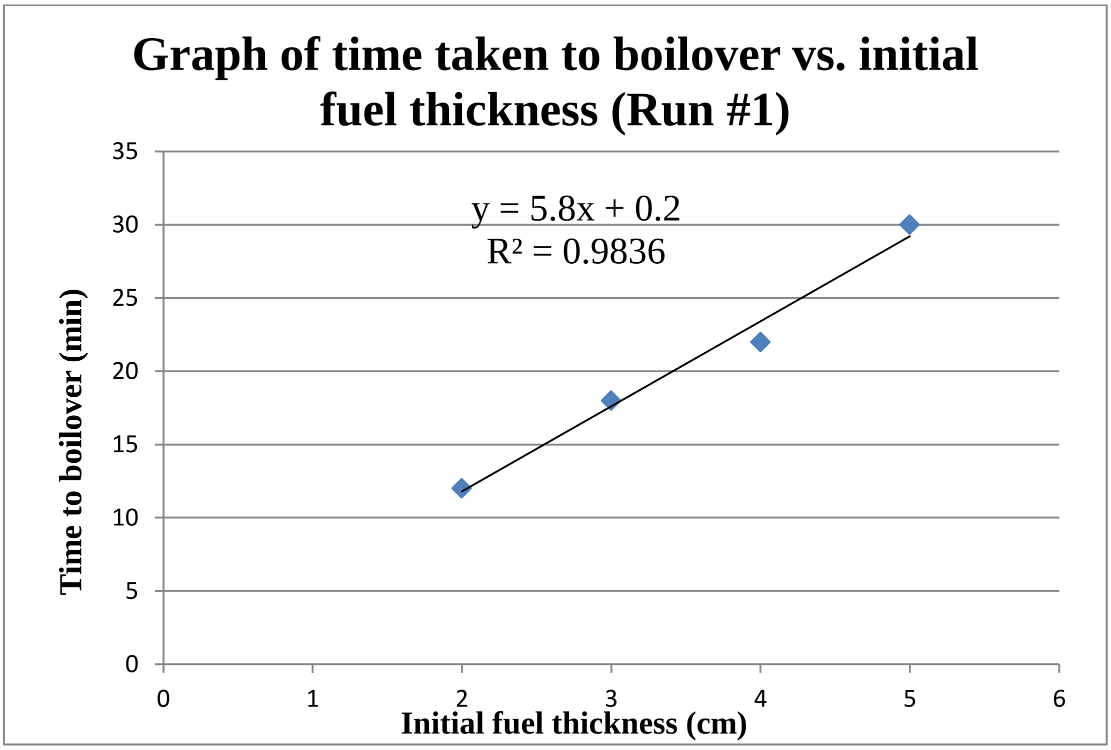
4.2 Effect of different fuel layer thickness

For the second part of the experiment, the one type of fuel composition is used that is 50% diesel and 50% petrol. The experiment is conducted by varying the fuel thickness from 2cm to 5cm. The time taken for boilover to take place for each experiment is recorded and is discussed in the later chapters. The results are shown in Table 3.

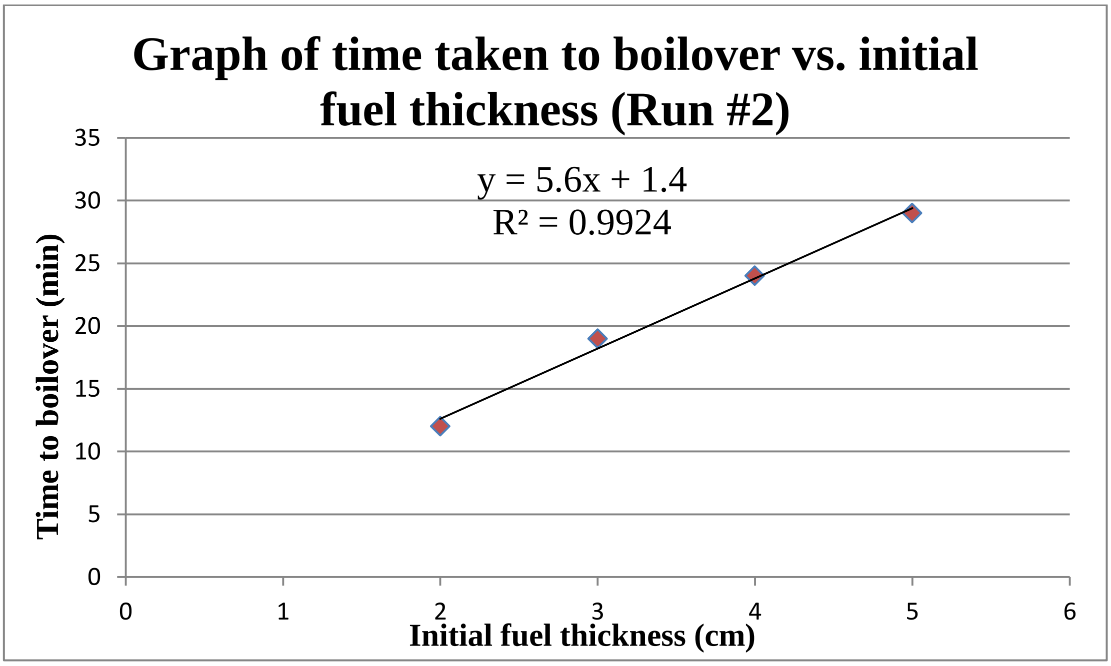
Table 3: Time Taken to boilover at various fuel thicknesses

Thickness of fuel layer, h_o (cm)	Volume (cm^3)	Fuel Type and Volume (cm^3)		Run #1 Time Taken for boilover (min)	Run #2 Time Taken for boilover (min)
		50% Petrol	50% Diesel		
2	568	284	284	12	12
3	850	425	425	18	19
4	1134	567	567	22	24
5	1418	709	709	30	29

It was observed that during the burning of the fuel, bubbles were formed on the surface signifying the vapourization of the component with the lower boiling point. The burning is seen to be less violent during the steady state burning. However, once the all the lighter components have been heated up and left with the heavier components on contact with the bottom of the tank, the flame is more intense. Towards to last burning phase, more vapour bubbles can be seen and loud cracking sound can be heard until the occurrence of a boilover. These observations correspond similarly to what has been observed in experiments conducted before by other researches on the larger scale basis.



Graph 1: Time to boilover (Run #1)



Graph 2: Time to boilover (Run #2)

The time taken to boilover increased as the initial fuel layer thickness increased. A plot of the time taken for a boilover against the initial fuel layer thickness is shown in Graph 1 and Graph 2. This is due to the fact that that the thicker the fuel, the longer it takes for the heat transfer process to boil the water layer at the bottom of the tank. As expected, the results show that the fuel layer thickness is linearly proportionate to time taken for the burning fuel to boilover.

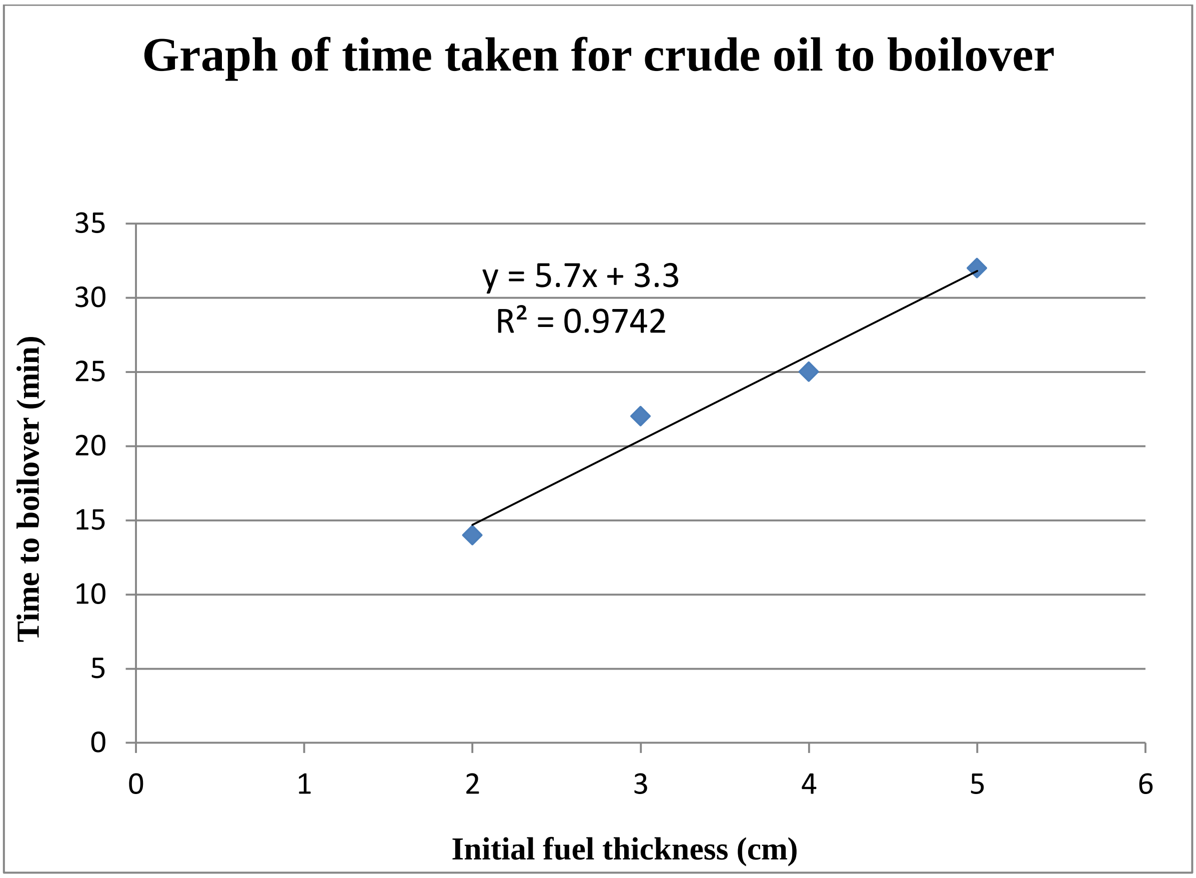
4.3 Effect of crude oil layer thickness on time to boilover

In addition to using the mixture of diesel and petrol as fuel, crude oil was used to study the effect it has on the time to boilover when the thickness of this fuel is varied. The experimental workup and procedure was carried out exactly as in section 4.2 with the only difference being the type of fuel used. The results of the experiment is recorded in the table below.

Table 4: Time Taken to boilover at various crude oil thicknesses

Thickness of fuel layer, h_o (cm)	Volume (cm^3)	Time Taken for boilover (min)
2	568	14
3	850	22
4	1134	25
5	1418	32

The same linear trend was observed when crude oil was used, as shown in Graph 3. The time taken for crude oil increased as the initial fuel layer thickness increased. However, the intensity of the boilover when the fuel layer was 4 cm and 5 cm was not as violent as expected and is less violent compared to when the fuel oil mixture was used. This may possibly be due to the fact that the crude oil that was used was stored for a long period of time and as a result of that, it isn't as viscous as it should be. Also, it is not certain whether the crude oil used was refined or not refined. These factors may have affected the results obtained for the time taken for crude oil to boilover.



Graph 3: Time taken for crude oil to boilover

All in all, based on all the experiments that were carried out for this study, the time taken to boilover increased as the fuel layer thickness increased. The regression line a correlation can be made of the experimental data where t_b represents the time to boilover (min) and h_o is the fuel layer thickness:

$$\mathbf{t_b = ah_o + b}$$

More time is required to heat up the bulk fuel to reach the boiling point temperature at the fuel-water interface This is due to the fact that that the thicker the fuel, the longer it takes for the heat transfer process to boil the water layer at the bottom of the tank.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The objective of this study was to contribute to the understanding of the boilover process. Considering the fact that a large-scale experimental set up would be hard to control and the risk and cost involved are large, this study aims to determine if a smale-scale study would be feasible. The significance of this is that, if the small scale study is indeed feasible, more scientist and researchers would duel in this topic thus extending the research development in this area. Therefore, a series of experiments were carried out to observe the effect of fuel composition as well as the initial fuel layer thickness on the time taken to boilover. There were no significant differences observed on the time taken to boilover when the proportion of diesel and petrol varied. However, moving on to the second part of the experiment when the fuel layer varied from 2cm to 5cm with the fuel composition of 50% petrol and 50% diesel, the time taken to boilover increased linearly. Finally, the thickness of crude oil was varied to observe the time for a boilover to take place, a similar linear trend was observed with the exception that the intensity of the boilover was less intense compared to the fuel mixture when the fuel layer thickness was 4 cm and 5 cm.

As a whole, the experiment was a success whereby the occurrence of the boilover process was effectlively replicated at a small scale. All the three periods of the boilover process that is the quasi-steady period, the premonitory period as well as the boilover period was observed clearly at each phase.The proceedings of the experiment are consist with the observations in the studies done and reported the literatures.

However, in terms of accuracy, an experiment at a small scale is not recommended particularly. The results obtained are valid for this particular experimental set-up and conditions and the exact correlation value may not be applicable for all boilover experiments. Thus, small scale study is suitable to study the mechanism of the boilover process to obtain a general and representation of the boilover process however, if precision is necessary, the experiment should be conducted on a larger scale.

5.2 Recommendations

The time taken for a burning fuel to boilover is influenced by many other factors like the fuel and water layer thickness, the diameter and material of the pan used. Therefore, coming up with any form of correlation based in a semi-empirical correlation seems inaccurate. Therefore, it is recommended that more parameters should be taken into consideration to develop a correlation for the time taken to boilover, for example, the temperature profile of the burning fuel as well as the burnt mass ratio. In addition to that, a larger diameter and height of the container should be used to obtain more readings to ensure that the linear trend recorded is justified.

In addition to that, experiments should be repeated at least three times to ensure that the findings are consistent and therefore it ensures accuracy and integrity of the findings.

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