A Study of Burning of a Thin Fuel Slick on Water with Waves.

A Major Qualifying Project

submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfilment of the requirements for the

degree of Bachelor of Science

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Executive Summary

This study analyzes the burning behavior of a liquid fuel floating on water with the interaction of waves. As In-Situ burning becomes a more viable way to clean up oil spills, it is increasingly important to study the combustion of liquid fuels floating on water. In this study, thin layers of kerosene poured into a circular, floating test pan were burned in a rectangular water-filled tank. The tank is equipped with a wave generator. Several initial fuel layer thicknesses and wave profiles were tested. Lower water sublayer and fuel/water interface temperatures were observed when waves were added, as well as increased total burn time. An upward trend in burning rate and burned mass ratio as wave steepness increases was also observed.

Introduction

As concern about oil spills has risen, so has the need for studies regarding in-situ burning. In-situ burning is a method of cleaning up oil spills where oil is gathered using fire-resistant booms and subsequently burned.[1] Due to the tradeoffs that come with this method of cleanup, a rather extensive process is taken to determine if in-situ burning is an appropriate response. As this process is refined and In-Situ burning becomes a more viable solution, the need for additional research into the combustion of liquid fuels floating on water rises.

Ocean waves are typically modeled as sine waves, and the vertical, circular motion of the water particles in an ocean wave is referred to as orbital motion. The diameter of this orbital motion decreases with the water depth, until it reaches the wave base. The wave base is located ½ the wavelength below the water level.[2] As a wave approaches shallower water, the shape of the orbital motion flattens. In order to replicate the decreasing diameter of orbital motion that is seen with deep ocean waves, a flapper-type paddle was used in the wave generator. There are two wave parameters that were particularly being observed with the variation in wave profiles. The first is the Froude number, which is a dimensionless parameter measuring the ratio of "the inertia force on an element of fluid to the weight of the fluid element".[3] It is calculated using equation 1. The second is the steepness, which is the wave height divided by wavelength and represents the slope of the front of the wave. The steepness is calculated using equation 2.[2]

$$U = \frac{\lambda}{\tau} \quad (1)$$

$$Fr = \frac{U}{\sqrt{gL}} \quad (2)$$

$$S = \frac{H}{\lambda} \quad (3)$$

These nondimensional parameters were chosen because they focus on different aspects of the wave. The Froude number includes wave velocity, U, and incorporates the effect the period value has on the wave. The wave velocity is calculated using equation 1. A key containing all the variables and their meanings is located at the end of this paper. Because the waves being simulated are deep ocean waves, the velocity is a function of wavelength. It provides a reference to how much resistance the pan has as it moves along the water. The greater the Froude number, the greater the resistance.[4] The wave steepness includes the wave height, an aspect of the wave that is not included in the Froude number calculation. Typically, the wave steepness is a parameter used to determine if a wave will break, however in the context of this research it is used to reflect on how wave height affects burning.[5]

Experiment

The experimental setup used composed of 26 K-type thermocouples attached to a 10-centimeter diameter test pan, a 2.4 meter long, 0.24 meter wide, and 0.28 meter tall tank filled with water, and two Sony RX10 cameras. A sketch of the tank and wave generator setup can be found in Figure 1a. The pan has a diameter of 10 centimeters and is a stainless-steel ring, connected to a Styrofoam ring to allow it to float. The Styrofoam ring is 5 centimeters wide and has an outer diameter of 20 centimeters, and the inner ring is 3.5 centimeters tall. A sketch of the pan and floating ring can be found in Figure 1b. The 26 thermocouples have been welded to the inner stainless-steel ring and are located 1.3 millimeters apart from each other. These can all be found pictured in Figure 2a, 2b, and 2c. Labview was used to record the data collected from the thermocouples. Screenshots of the VI file can be found in Appendix A. The front panel contained a record data button, waveform chart display, and a timer. These aid in recording the exact time to boilover during the experiments if it occurred. DAQ assistant was used to connect the thermocouples, which are set to write to a chosen excel file.

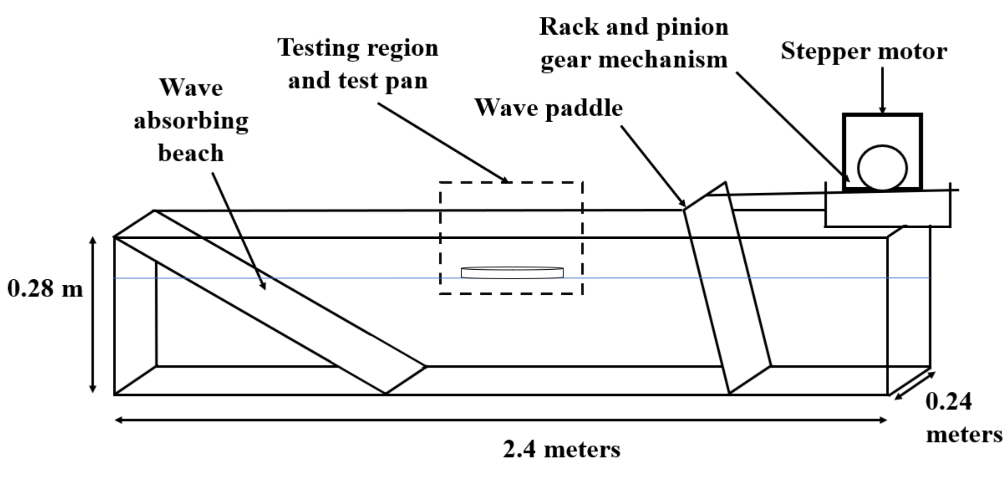


Figure 1a: Sketch of experimental Set-up.

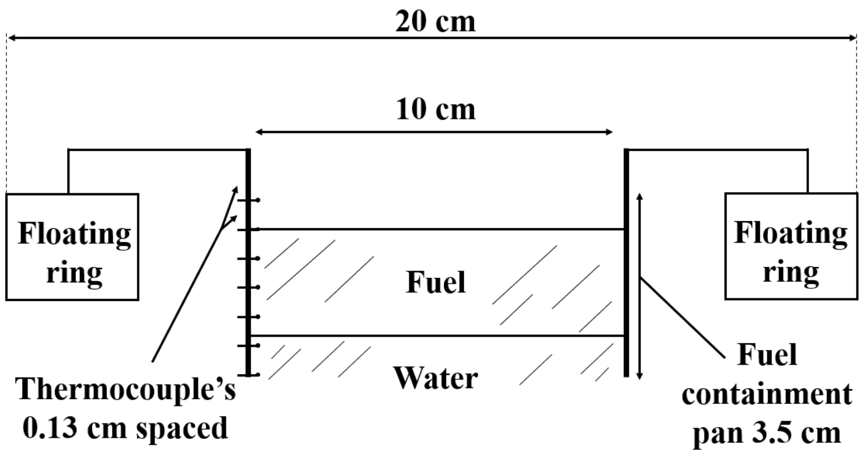


Figure 1b: Sketch of cross section of fuel pan and floating ring.

Figure 2a: Photo of overall tank set-up.

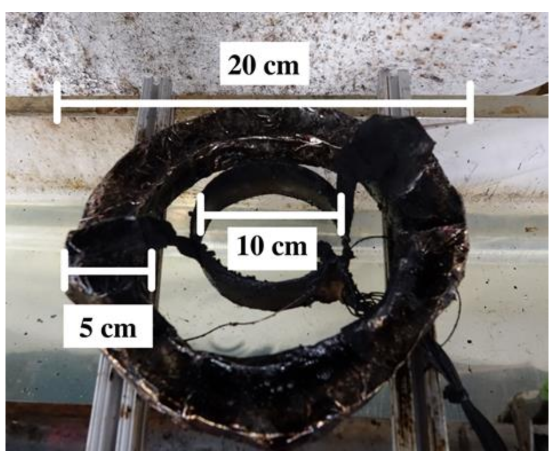


Figure 2b: Photo of pan and floating ring.

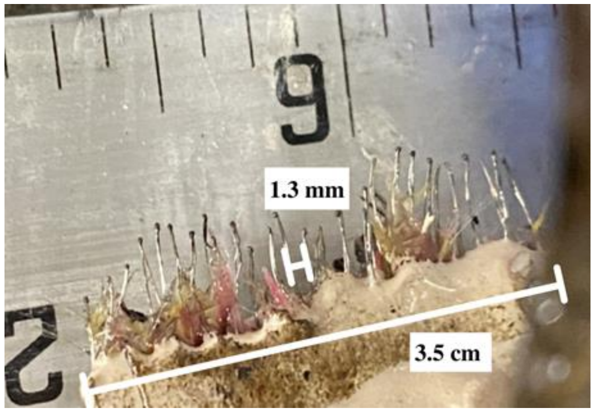


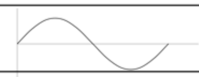
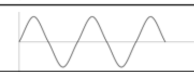
Figure 2c: Photo of thermocouple spacing.

To control the wave generator, which is pictured on the right side of the tank in figure 2a, Tera term is used. The wave generator requires an input wave height and period. The wave generator itself is made up of a stepper motor, pinion gear, and rack gear and is driven by a program that has been written in Arduino.

In all experiments, kerosene was used as the fuel. Kerosene is known to have a boiling point range of 158-325 $^{\circ}$C. [6] The kerosene used in this collection of experiments had an average density of 0.765 grams per milliliter.

Experiments were conducted in two phases. The first phase was testing varying initial fuel layer thicknesses from 0.2 centimeters to 2 centimeters, with no waves to set a baseline for future experiments with waves. The second phase was testing varying wave profiles at a set initial fuel layer thickness of 0.6 centimeters. These wave profiles are detailed in Table 1.

Table 1: Wave profile matrix.

Steepness	Wave Height [m]	Period [s]	Wavelength [m]	Froude Number	Visual [Duration = 1s]
0.003	0.003	1	1.18	0.63	
0.004	0.01	2	2.6	1.31	
0.008	0.02	2	2.6	1.31	
0.008	0.01	1	1.18	1.19	
0.012	0.003	0.4	0.25	0.63	
0.013	0.005	0.5	0.3882	0.78	
0.017	0.02	1	1.18	1.19	
0.040	0.01	0.4	0.25	0.63	
0.080	0.02	0.4	0.25	0.63	

Results

Visual Timeline:

Figure 3 contains three timelines. All three timelines contain timestamps at similar points in each experiment. The first timeline shows the no-wave case, along with its boilover. The second timeline shows a case with a 1-centimeter-tall wave and period of 2 seconds. This is one of the waves with the highest Froude number, and one of the lower steepness values of all the experiments. The third timeline shows a case with a 2 centimeters tall wave and period of 0.4 seconds. This is one of the waves with the lowest Froude number, and the highest steepness value of all the experiments. These two waves represent "extreme" wave cases on opposite sides of the spectrum.

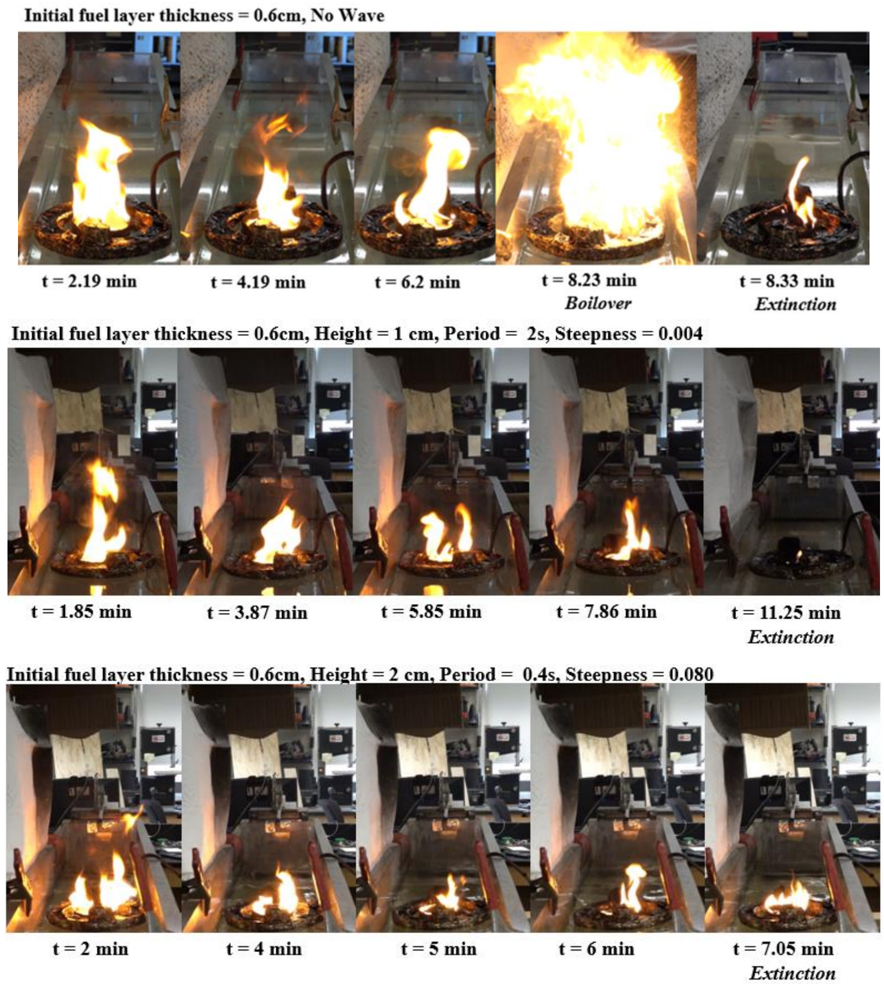


Figure 3: Visual timelines for three different wave profiles.

As can be observed in Figure 3, the cases with the addition of waves demonstrated no boilover, and visibly smaller flames. For comparison, a sketch of the behavior of a no-wave experiment can be found in Figure 4a. Between the two wave extremes, we can see that not only does the case with a higher Froude number and lower steepness have a larger flame, but also sustains burning longer than both the no wave and low Froude number, high steepness wave case. A sketch of the low steepness, high Froude number wave case behavior can be found in Figure 4b. The flame of low Froude number, high steepness wave case also exhibits a unique flame “splitting” behavior, where it is essentially hugging the sides of the area within the pan. A sketch of this splitting behavior can be found in Figure 4c. The wave is likely moving the kerosene located in the center of the pan, causing the flame to have a difficult time propagating in the center. This flame “splitting” behavior was only observed in the experiments using the highest wave steepness.

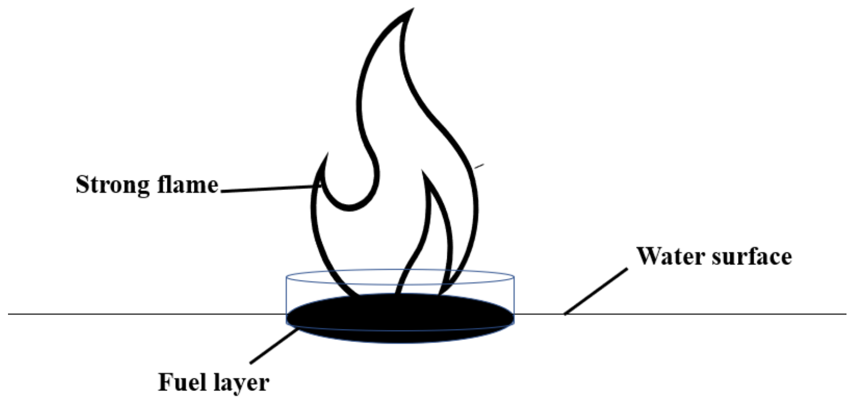


Figure 4a: Sketch of no-wave condition burning.

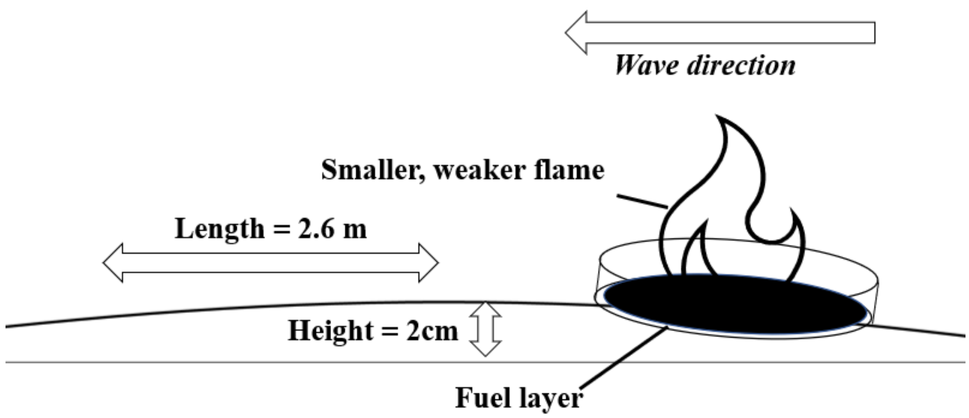


Figure 4b: Sketch of effect of low steepness wave on flame.

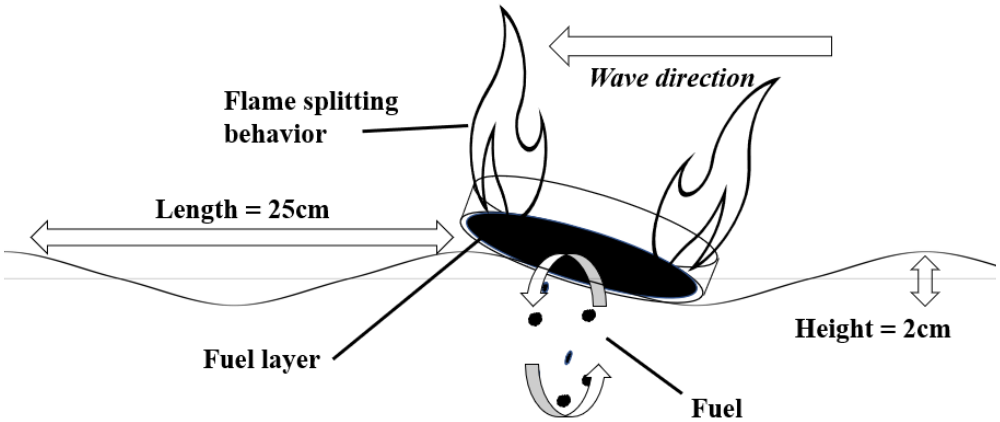


Figure 4c: Sketch of effect of high steepness wave on flame and fuel layer.

Average Burn Time:

Table 2 shows the average burn time for all wave profiles. It can be observed that for all waves except the 2 centimeters height and 0.4 second period wave, the burn time is longer than the no-wave case. This is likely because the no wave case experiences boilover, which causes fuel to become ejected and therefore, shorten total burn time. The 2 centimeters height and 0.4 second period wave likely experienced a lower average burn time due to fuel being visibly carried away from the pan from the start of the experiment. This was the only wave profile where this behavior was observed. A sketch of this observed behavior can be found in Figure 4c. It should be noted that this wave has the lowest Froude number, and highest steepness out of all wave profiles tested. This observation may be connected to the flame-splitting behavior observed in the same experiments. If the kerosene is swept underneath the pan, it is also going through a heating- cooling process, making is more difficult for the fuel in the center of the pan to heat up enough to propagate flames.

Table 2: Average burn time.

Wave Profile	Steepness	Froude Number	Total Burn Time, Average [min]
No Wave	0	0	8.96
Height: 0.5cm Period: 0.5s	0.013	0.78	10.53
Height: 1cm Period: 2s	0.004	1.31	11.5
Height: 2cm Period: 2s	0.008	1.31	11.16
Height: 0.3cm Period: 1s	0.003	1.19	9.05
Height: 1cm Period: 1s	0.008	1.19	11.07
Height: 2cm Period: 1s	0.017	1.19	10.35
Height: 0.3cm Period: 0.4s	0.012	0.63	9.32
Height: 1cm Period: 0.4s	0.040	0.63	10.8
Height: 2cm Period: 0.4s	0.080	0.63	7.74

Liquid Temperature History:

Figures 5 and 6 show the temperatures plotted against the depth relative to the fuel/water interface for a no-wave case, and the two extreme wave cases for several timestamps. Figure 5 is the no-wave case. It can be observed that the fuel/water interface reaches approximately 120°C at Boilover. Figure 6 is temperature data for a wave profile of 2 centimeters height and 0.4 second period. This case has the lowest Froude number and highest steepness. The interface reaches an approximate temperature of 75°C at its highest. When comparing these two cases, it can be observed that waves have almost an inverting affect on temperatures. In the no-wave case, as time increases, so do temperatures. However, when waves are added, this is inverted, where as time increases past 5 minutes, the temperatures decrease as time goes on. Additional figures for each experiment are located in Annex C.

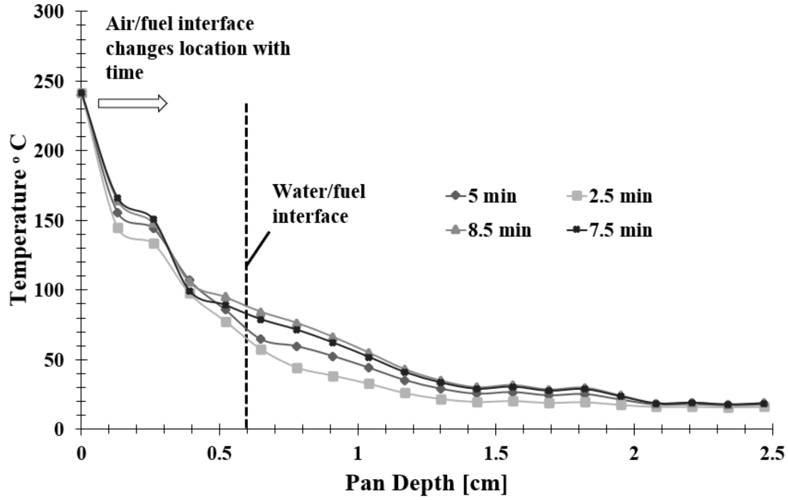


Figure 5: Temperature vs. Depth chart for a no-wave case, 0.6 cm initial fuel layer thickness.

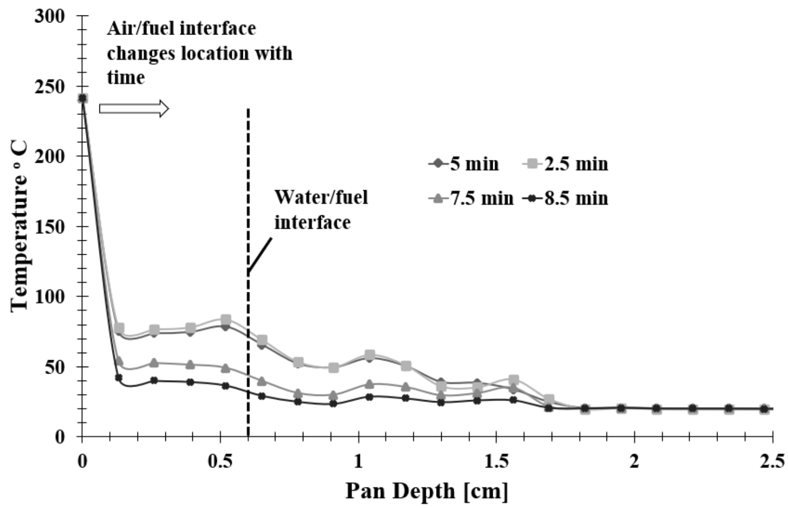


Figure 6: Temperature vs. Depth chart for a 2 cm wave height and 0.4 s period case, 0.6 cm initial fuel layer thickness.

Burned Mass Ratio:

Figure 7 shows the burned mass ratio plotted against the wave profile steepness. For clarity, a cluster of points between steepness values of 0 and 0.01 were omitted from the chart. No chart comparing the Froude number is shown because no clear trend was found. Burned mass ratio was calculated using the recorded values for initial and final mass, and equation 4.

$$Burned\ mass\ ratio = \frac{mass_{burned}}{mass_{initial}} \qquad (4)$$

The point plotted at a steepness of 0 is the no-wave case average. As steepness increases, the burned mass ratio decreases. When the steepness surpasses 0.008, higher burned mass ratios are calculated. This is counterintuitive, because visually a smaller flame is observed. It is likely that as wave steepness increases, more fuel is carried away from the bottom of the pan (Figure 4c). This would explain a higher calculated burned mass ratio, when the flame is not only smaller, but also in some cases showing splitting behavior (Figure 4c). If fuel is carried out of the pan, less fuel will be contained in the pan post-burn, causing the burned mass ratio to seem higher, when it should not be. Error bars representing the standard deviation are included for each data point, and a discussion on error can be found in Annex C, and sample calculations can be found in Annex D.

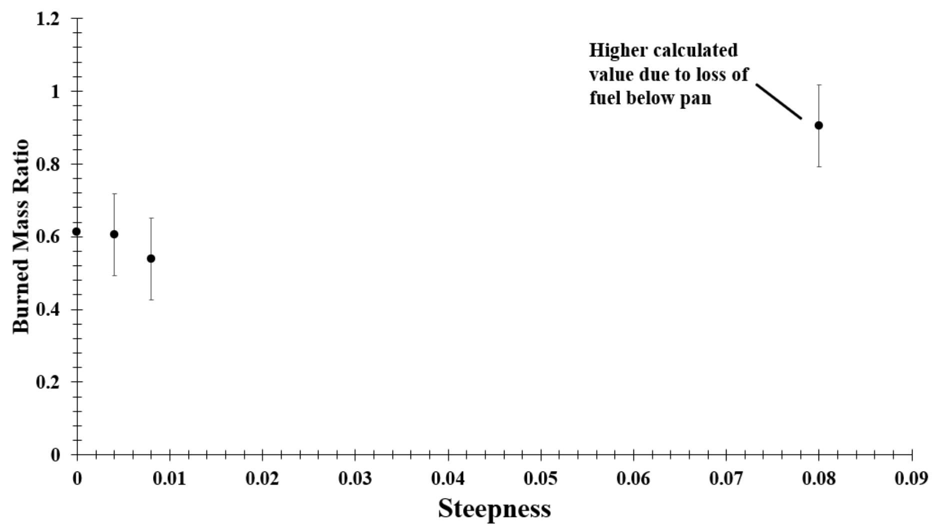


Figure 7: Burned mass ratio plotted against wave steepness.

Discussion

The key to understanding the effects wave have on combustion behavior lies in the dT/dx values at the interface for each wave profile. To obtain these curves, a logistic fit method was used. The general form of the fitting equation was:

$$y = \frac{a}{(b + c * e^{dx})} \quad (5)$$

Values for a, b, c, and d were used to calculate a set of predicted temperature values. The standardized error for each plot point was calculated and added together. Excel solver was used to minimize the total standardized error by changing the values of a, b, c, and d. These were plugged into equation (5), which was subsequently differentiated to obtain an equation for dT/dx. Sample calculations for this process can be found in Annex D. The absolute value of these values was then plotted. Figure 8 contains the dT/dx vs. pan depth for the no wave case at several times. For this case, as time increases, the dT/dx overall curve increases. Figure 9 contains the dT/dx vs. pan depth for the low Froude number, high steepness case. For this case, within the first 5 minutes, the overall curve stays relatively the same, however at times beyond that, the curve decreases significantly. This is the same kind of inverting behavior that was observed with the temperature vs. depth charts.

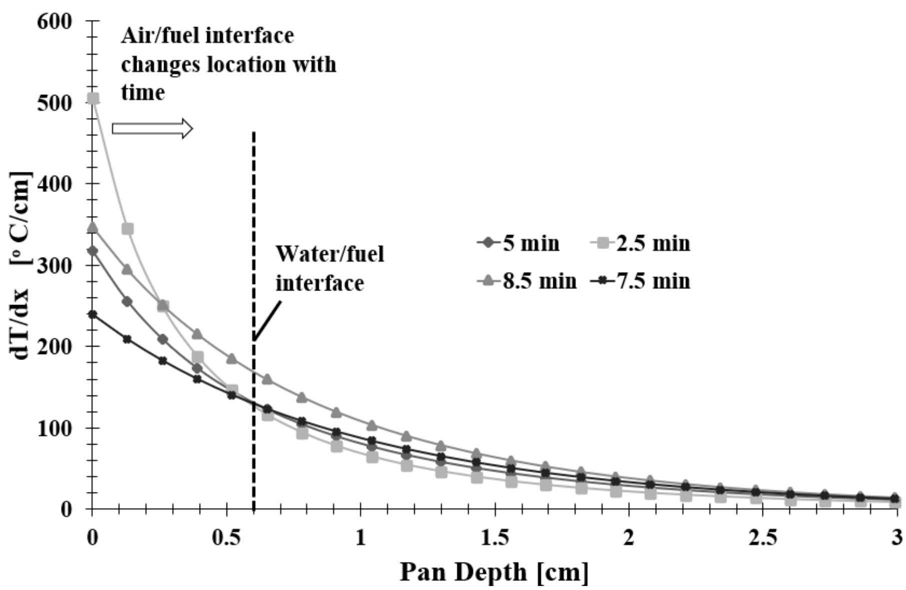


Figure 8: dT/dx vs. pan depth, no wave case, 0.6 cm initial thickness.

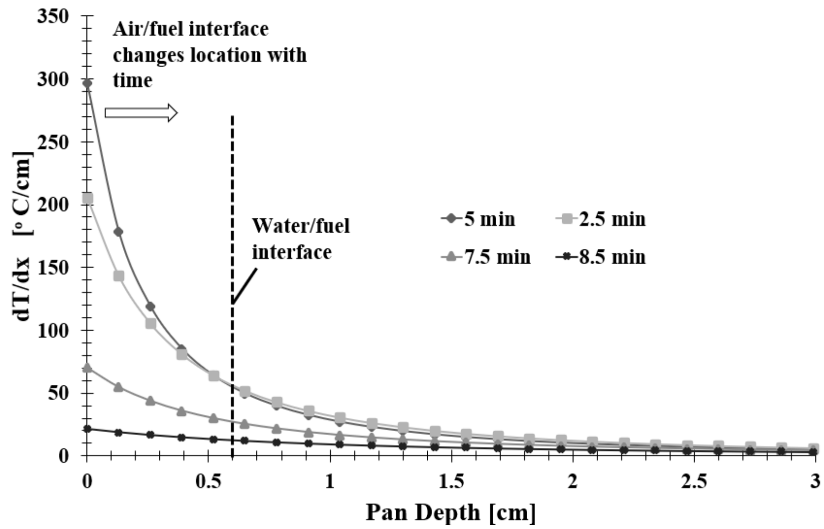


Figure 9: dT/dx vs. pan depth, 2 cm height 0.4 s period wave case, 0.6 cm initial thickness.

The dT/dx values can be graphed as a function of S/Fr number to capture the effects of wave speed and wave period. Figure 10 shows this relationship. As seen in the plot, there is a relatively linear relationship between these two values. For clarity, a cluster of data points between S/Fr values of 0 and 0.02 have been omitted from this chart. For this chart, all values were obtained at the 2.5-minute mark for all experiments. This was done to guarantee that all experiments were sustaining burning at the selected timestamp. A general downward, somewhat linear trend is observed as steepness increases. This ties into the inverting behavior that has been observed previously.

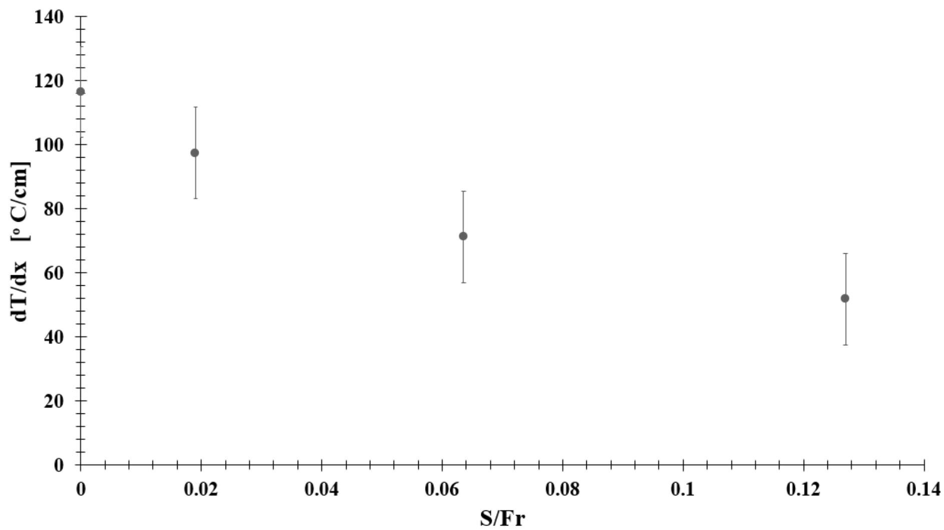


Figure 10: dT/dx plotted as a function of S/Fr.

These dT/dx values can be used to approximate the regression rate of the fuel via a method detailed by F. Williams in Chapter 3 of *"Heat Transfer in Fires: thermophysics, social aspects, economic impact"*.[7] The following expression can be obtained by applying equation 6 to equation 7 by defining $\dot{q} = \dot{q}_R + k(\frac{dT}{dx})$ as the total energy per unit area per second transmitted to the fuel surface. Note that the (+) subscript denotes above fuel surface and the (-) subscript denotes below the fuel surface.

$$\rho_+ v_+ L_s = (\frac{kdT}{dx})_+ - \left(\frac{kdT}{dx}\right)_- + \dot{q}_R \quad (6)$$

$$\theta = \theta_s e^{r\xi} \quad (7)$$

$$\frac{dT}{dx_{0-}} = (T_s - T_\infty)\frac{r}{\alpha} \quad (8)$$

T_s and T_∞ as well as α [for kerosene, calculated $\alpha = 8.7964\text{E-}08\ m^2/s$] are constant throughout the fuel layer. Therefore, the regression rate can be treated as a function of dT/dx. Figure 11 shows the general trend that was observed for calculated regression rate against wave steepness. The trend observed was a very linear downward trend as wave steepness increases. Sample calculations can be found in Annex D.

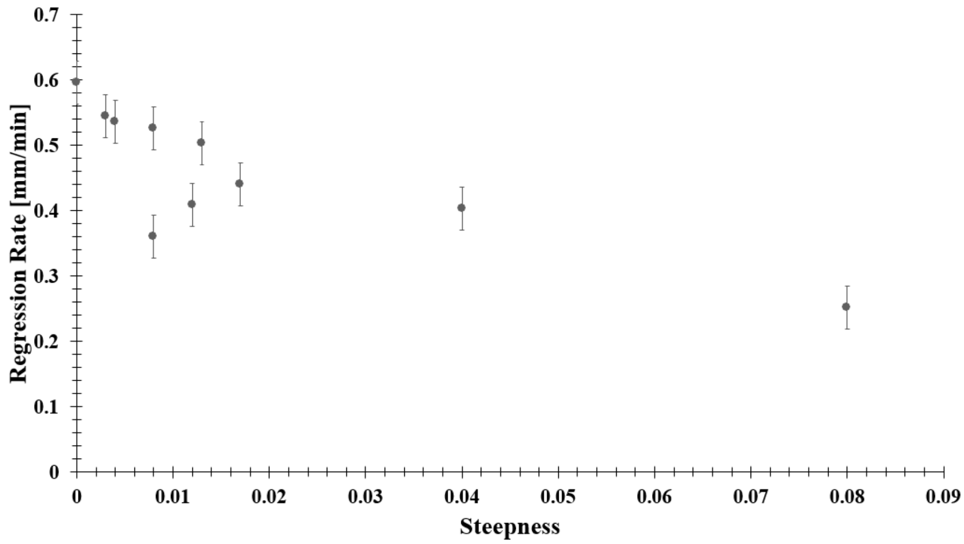


Figure 11: Calculated Regression Rate as a function of wave steepness.

Conclusion

There are several key takeaways from this research. It was found that Boilover does not occur when waves impact combustion of floating fuels on water with a 10 cm diameter burn area. The two wave parameters that appear to have the most impact on the burning is the wave steepness and particularly wave height.

It was also found that an inverting behavior occurs in temperature data when waves are introduced. When waves are added, temperatures decrease over time vs. in the no wave case, temperatures increase until Boilover occurs. At the lowest Froude number and highest steepness, fuel is visibly observed to be circulated outside of pan by wave orbital motion, and a flame splitting behavior is observed. Using calculated dT/dx values, a downward linear trend between wave steepness and regression rate can be obtained.

The next step with this data would be to correlate wave steepness with wave orbital size via existing research, or experiments in the tank.

Abbreviations Key:

S = wave steepness

Fr = Froude number

α = thermal diffusivity

λ = wavelength

τ = wave period

g = acceleration due to gravity

l = characteristic length

H = wave height

r = regression rate

T_s = Surface temperature of kerosene

T_∞ = Ambient temperature

$\dot{q}_R$ = net radiant energy per unit area per second absorbed at the surface

ρ = density

v = non-dimensional regression rate

L_s = Heat of gasification of fuel per unit mass at surface temperature

θ = non-dimensional temperature

ξ = axis, nondimensional coordinate

k = coefficient of thermal conductivity

Works Cited

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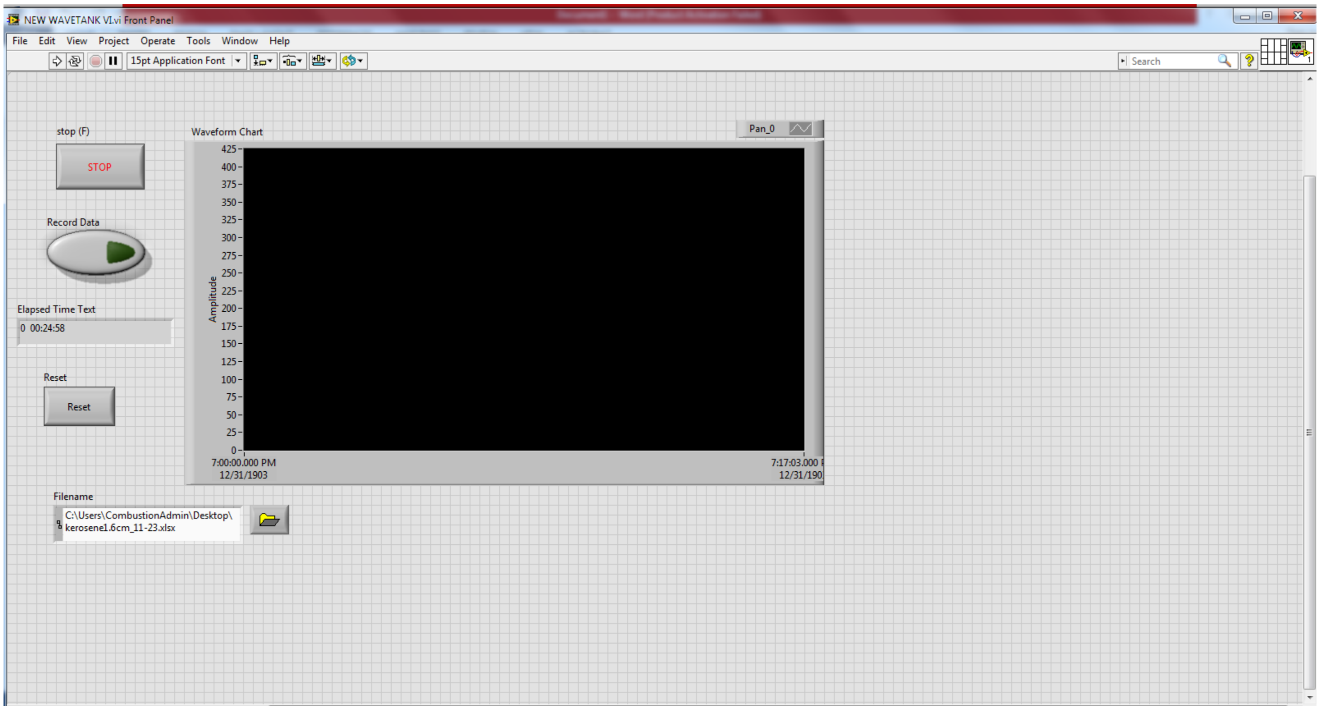
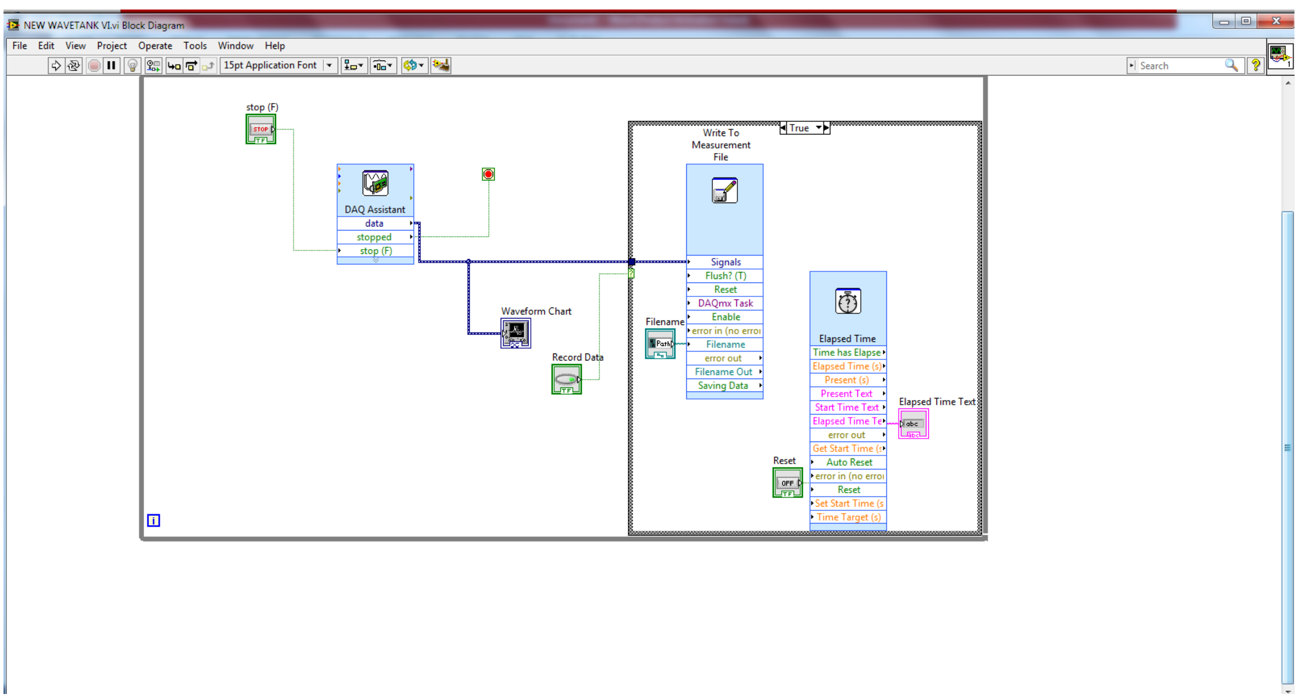
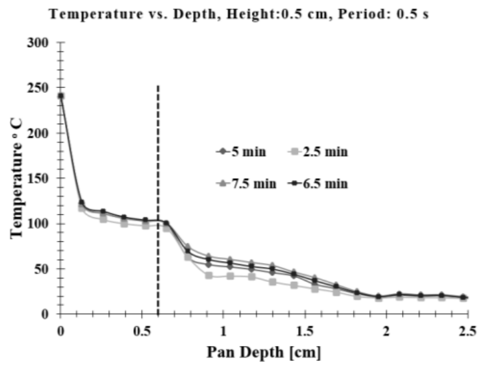
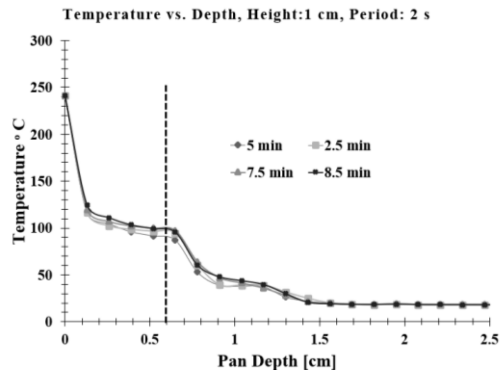
Annex A: Labview VI

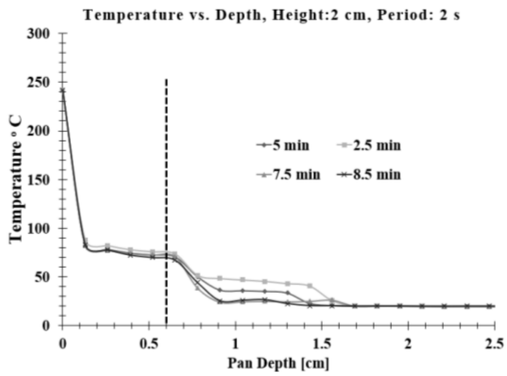


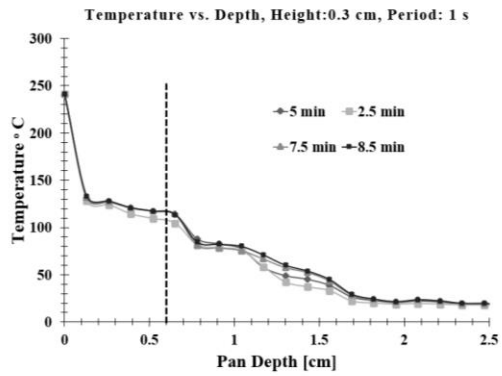


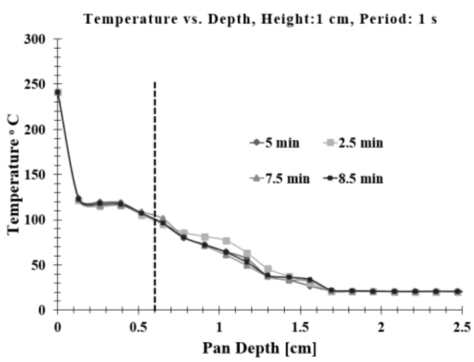
Annex B: Temperature/depth charts for one of each experiment

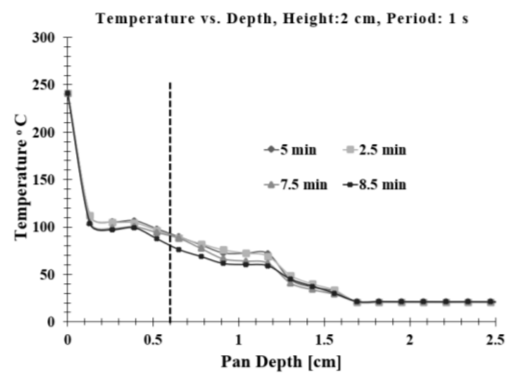


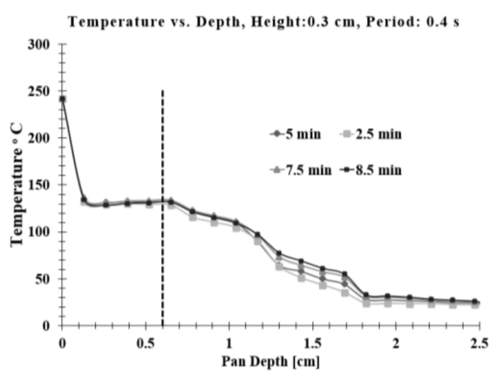


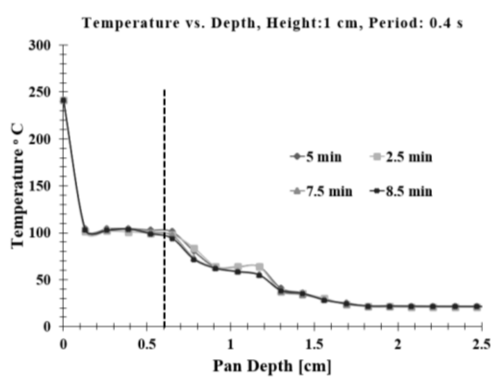












Annex C: Error

It's important to note any error in both measurements and calculations for these experiments. Charts with calculations involved all contain error bars that represent standard error, or standard deviation.

There is also an amount of human error that could have occurred with these experiments. Some notable sources of error could be: excess water on absorbent pads when measuring post-burn mass, vent hood interference with scale, drops of fuel splashing outside of pan when being poured, and excess mass from the test pan falling off and into the test pan during the experiment.

Some thermocouple data points were replaced by interpolation due to incorrect reading, or the thermocouple being broken at the time of experiment. A few tests had to be thrown out due to the wave generator overheating.

Annex D: Sample calculations

Burned mass ratio.

$$Burned\ mass\ ratio = \frac{mass_{burned}}{mass_{initial}}$$

Example: Height 0.5 cm, Period 0.5 s case

Pre-burn mass = 35.99 g

Post-burn mass = 13.06 g

Amount burned = 36.99 – 13.06 = 22.93 g

Burned mass ratio = 22.93/35.99 = 0.64

dT/dx.

As described in the discussion section of paper, the Temperature vs. Pan Depth data was fit to the following equation using a logistic fit method.

$$Estimated\ value = \frac{a}{(b + c * e^{dx})}$$

Data inputted into excel, for each data point the normalized error is calculated for each data point using the following formula:

$$Normalized\ error = \frac{Estimated\ value - actual\ value^2}{Actual\ value}$$

The normalized error for each data point is summed, and then excel solver is used to minimize this value by changing constants a, b, c, and d.

The function that is generated is then differentiated, and x values are plugged in to generate dT/dx values.

Example: Height 0.5 cm, Period 0.5 s case at 2.5 min

Normalized error sample calculation for one point:

Actual point value = 122.6 C at x = 0.13

Normalized error = (Arbitrary number-122.6/122.6) = Normalized error

Excel solver output: a = 27.35, b = -0.55, c = 0.69, d = 0.44

This gives function of:

$$y = \frac{27.35}{(-0.55 + 0.69 * e^{0.44x})}$$

Differentiated, this equation equals:

$$y'(x) = \frac{17.48e^{0.44x}}{(0.8 - e^{0.44x})^2}$$

Plugging this into our original data point, we obtain a dT/dx value of:

dT/dx = 17.48*e^(0.44*0.13)/(0.8-e^(0.44*0.13))^2 = -283.4 $^{\circ}$C/cm

Regression Rate:

Building on top of the previous calculation, we can obtain the regression rate by solving for r in the following equation:

$$21104.5 = (241.5 - 20)\frac{r}{8.8E - 08}$$

We choose a dT/dx value that is from inside the fuel layer. It also needs to be in the correct units. We obtain r = 5.89*10^-5 m/s