Liquid Fuel Burning Behavior in Ice Cylinders

A Major Qualifying Project Report

Submitted to the Faculty
of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science
in
Chemical Engineering

June 1st, 2012

Submitted by:

Shigeng Shang

Approved by

Professor Ali Rangwala

Acknowledgement

I would like to extend my sincere thanks to my advisor Professor Ali S. Rangwala for his tireless guidance and support. Also I am grateful for all the help I got from Kulbhushan Joshi, Scott Rockwell, and Xiaochuan (Lydia) Shi in the Combustion Lab of Fire Protection Engineering Department, WPI.

Table of Contents

Table of Figures

Introduction

The continually rising high demand for petroleum has made the US government and petroleum industry more interested than ever in the potential of drilling oil in the Arctic and subarctic regions. Exxon Mobil and the Russian oil firm Rosneft signed a deal in August 2011 to drill on Russia's Arctic Sea shelf and in the deep waters of the Black Sea (Englund and Plumer 2011). Shell Gulf of Mexico Inc. hopes to begin exploratory drilling in the Chuckchi Sea and Obama administration has approved its oil spill response plan (Murphy 2012) (Shell 2011). In this plan, *in situ* burning is one of the major methods to clean up spilled oil. The present of ice made oil spill in Arctic region a unique situation compare to the standard oil spill response on calm sea water. Little research has been done on fuel burning in direct contact with ice. Thus in depth research on such subject is required. Peter W. Bellino has done bench-top experiments on *in situ* burning of oil in an ice channel and concluded that the efficiency of fuel burning highly depends on the amount of remaining fuel during burning and fuel layer depth. (Bellino 2012) This Major Qualifying Project is a spin-off of Bellino's experiments. The goal is to examine how fuel behaves in *in situ* burning within a cylindrical ice container; aspects include the mass loss and mass loss rate of fuel, temperature profile of fuel and the wall of melting ice cylinder, and the relationship of overflow in one inch inner diameter ice cylinder and fuel quantity.

Methodology

Creating Ice Cavities

Different diameters of Charlotte™ PVC pipes were chosen as the molds for the cylindrical ice cavities. A 4-inch inner diameter PVC pipe was used as the container. One end of the pipe was left open; the other end was sealed tightly with multiple layers of heavy duty duct tape to provide a flat surface and to prevent water leakage. Pipes with inner diameters of 0.5-inch, 1-inch, 1.5-inch and 2-inch with one end sealed were inserted individually in the center of the container to create the cylindrical cavities. Pipe fitting components were utilized to make sure the inner pipe stayed in the center of the outer pipe. Once water froze in this two-part mold, an ice cavity with variable inner diameters was formed. Due to the thick walls of the PVC pipes, the inner diameters of the ice cavities were not as the same as the center pipe's inner diameter. Table 1 below shows the actual measurements of each ice cavity.

Table 1: Comparison of PVC pipes' manufacture standard inner diameters and diameters used as ice cavity molds

Pipe	Inner Diameter (inch)	Ice Cavity Diameter (inch)	Ice Cavity Diameter (cm)
I	0.5	0.83	2.10
II	1	1.31	3.33
III	1.5	1.89	4.80
IV	2	2.40	6.10

The ice cavity was then sawed to be 10 cm in depth. It was frozen again to be attached to a solid ice base. The base was made in the 4-inch PVC pipe with no hollow center. It did not require specific dimensions but was usually 2-3 inches deep. This depth guaranteed enough ice on the bottom so fire would not melt through to cause loss of fuel. The base also served as a stabilizer of the ice cylinder.

For once there were 5 type K thermocouples (0.125 cm diameter) frozen inside of the wall of an ice cylinder made with 2-inch inner diameter PVC pipe. To place the thermocouples, 2 mm diameter holes were drilled 2 cm apart from each other on one side of an aluminum angle. There were 5 holes on the aluminum angle. The lowest one was 2 cm from the bottom end of the angle. For each thermocouple, one end of it was bent and hooked to the hole; the other end extended upwards along the aluminum angle, and was connect to a data acquisition device, which collected and logged data to the laptop. At the center of the ice cavity, there was another exact aluminum angle with 5 thermocouples held by a clamp. The purpose of these thermocouple arrays was to measure the temperature during the melting process of the wall and in the center of the fire, respectively.

Experimental Setup

The ice cylinder was placed in an aluminum tray so that the water would not run off. The tray was placed on a load cell, which was connected to a laptop to measure and record the mass changes during fuel burning. The fuel was a mixture of three parts of SAE 30 motor oil (BP Lubricants USA Inc. 2010) and one part of petroleum ether (EMD Chemicals Inc. 2010) to simulate crude oil. Table 2 is a list of physical properties of the oil mixture. (Bellino 2012)

Table 2: Properties of Oil Mixture

Density	ρ	884 kg/m^3
Flash Point	T_{ft}	161 °C
Boiling Point	T_{bp}	236 °C
Thermal Conductivity	k	0.146 W/m·K
Specific Heat	C_p	1.912 J/kg·K
Thermal Diffusivity	α	905x10^{-7} m^2/s

The amount of oil poured in each cylinder was determined by the depth of the oil layer. It was 2 cm thick for all the tests, except when the overflow tests for 1-inch inner diameter ice cavities were run, the quantity of fuel was increased by volume to determine how much fuel was needed to melt the ice wall completely without excess fuel.

Figure 1 is an empirical presentation of the ice cavity and experimental setup.

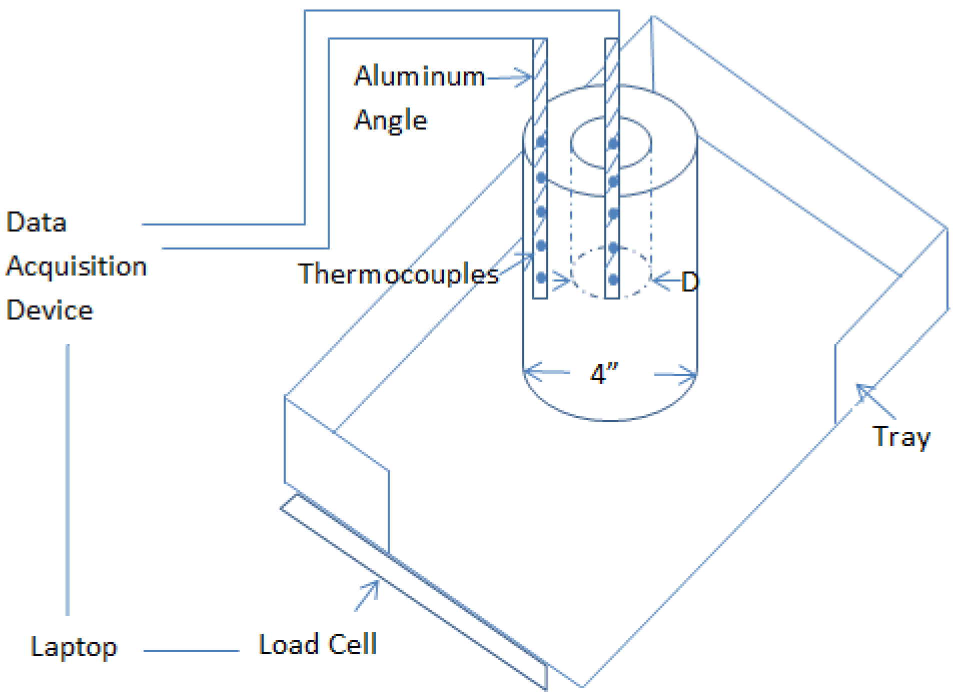


Figure 1: A diagram of the experimental setup

Results and Discussion

Mass Loss Rate

Mass loss of fuel during the *in situ* burning in ice cylinders with different inner diameters was measured and logged. The data was plotted with respect of time and a 6^{th} order polynomial trend line as fitted to illustrate the tendency. For each different inner diameter of ice cavity, there was an equation of mass loss as a function of time, and r^2represents the burning efficiency of the fuel. All the tests have shown an upward trend line. After the ignition, fuel went through combustion process as time passed; releasing heat to melt the ice it had contact to.

Half inch

$$dM = -7 \times 10^{-13}t^6 + 5 \times 10^{-10}t^5 - 1 \times 10^{-7}t^4 + 1 \times 10^{-5}t^3 - 0.0002t^2 + 0.0135t + 0.3994$$

$$r^2 = 0.8947$$

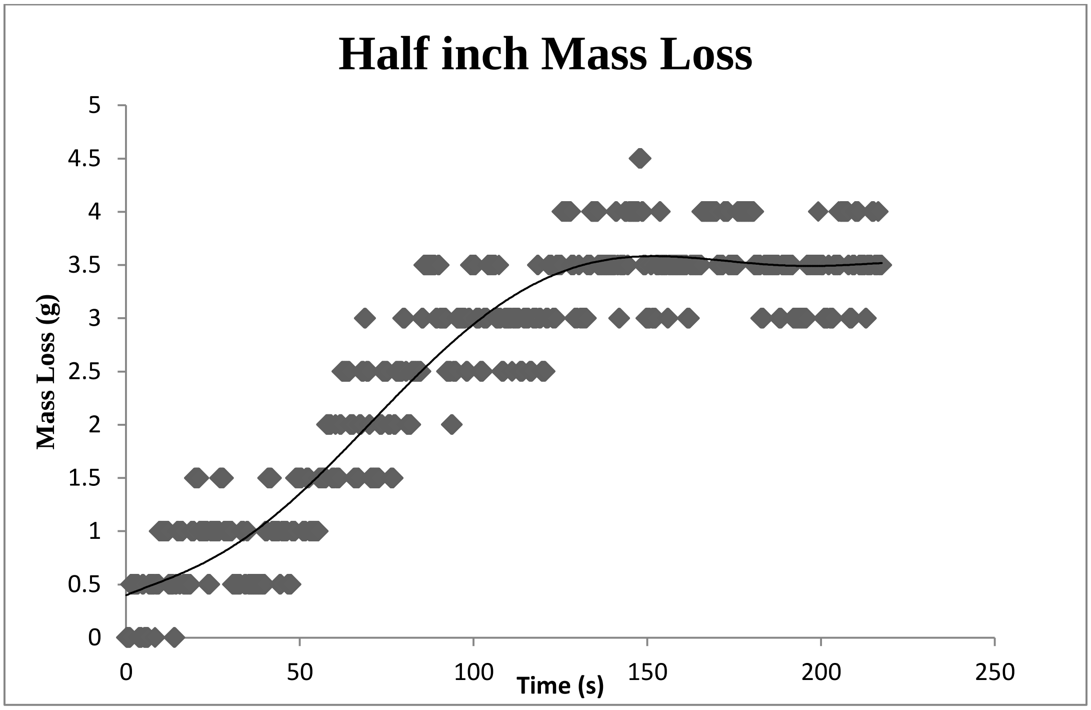


Figure 2: Mass loss of fuel in half inch inner diameter ice cylinders

One inch

$dM = 2 \times 10^{-12}t^6 - 1 \times 10^{-9}t^5 + 1 \times 10^{-7}t^4 - 3 \times 10^{-6}t^3 - 0.0007t^2 + 0.0501t + 0.181$

$r^2 = 0.7844$

Figure 3: Mass loss of fuel in one inch inner diameter ice cylinders

One and half inch

$$dM = -2 \times 10^{-13}t^6 + 2 \times 10^{-10}t^5 - 8 \times 10^{-8}t^4 + 2 \times 10^{-5}t^3 - 0.0012t^2 + 0.0442t + 0.4904$$

$$r^2 = 0.9359$$

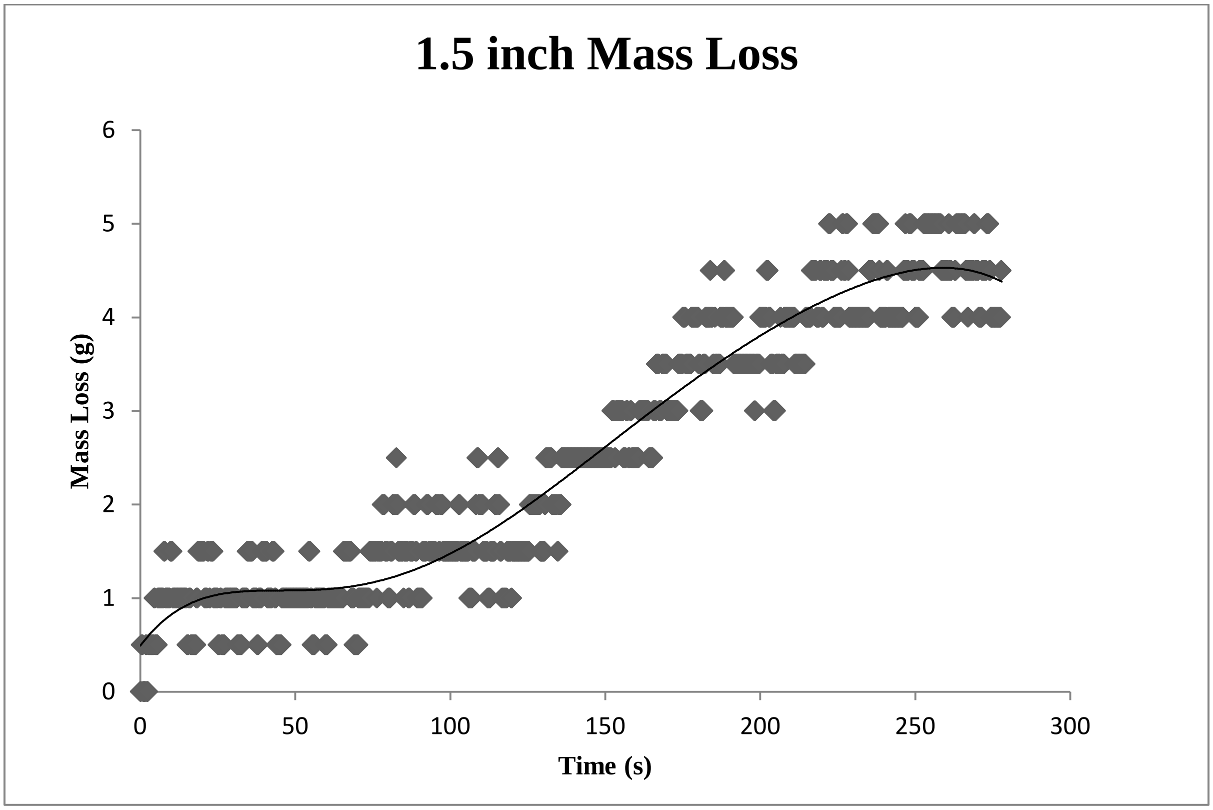


Figure 4: Mass loss of fuel in one and half inch inner diameter ice cylinders

Two inch

$$dM = -6 \times 10^{-11}t^6 + 2 \times 10^{-8}t^5 - 3 \times 10^{-6}t^4 + 0.0002t^3 - 0.0048t^2 + 0.0769t + 0.6359$$

$$r^2 = 0.7216$$

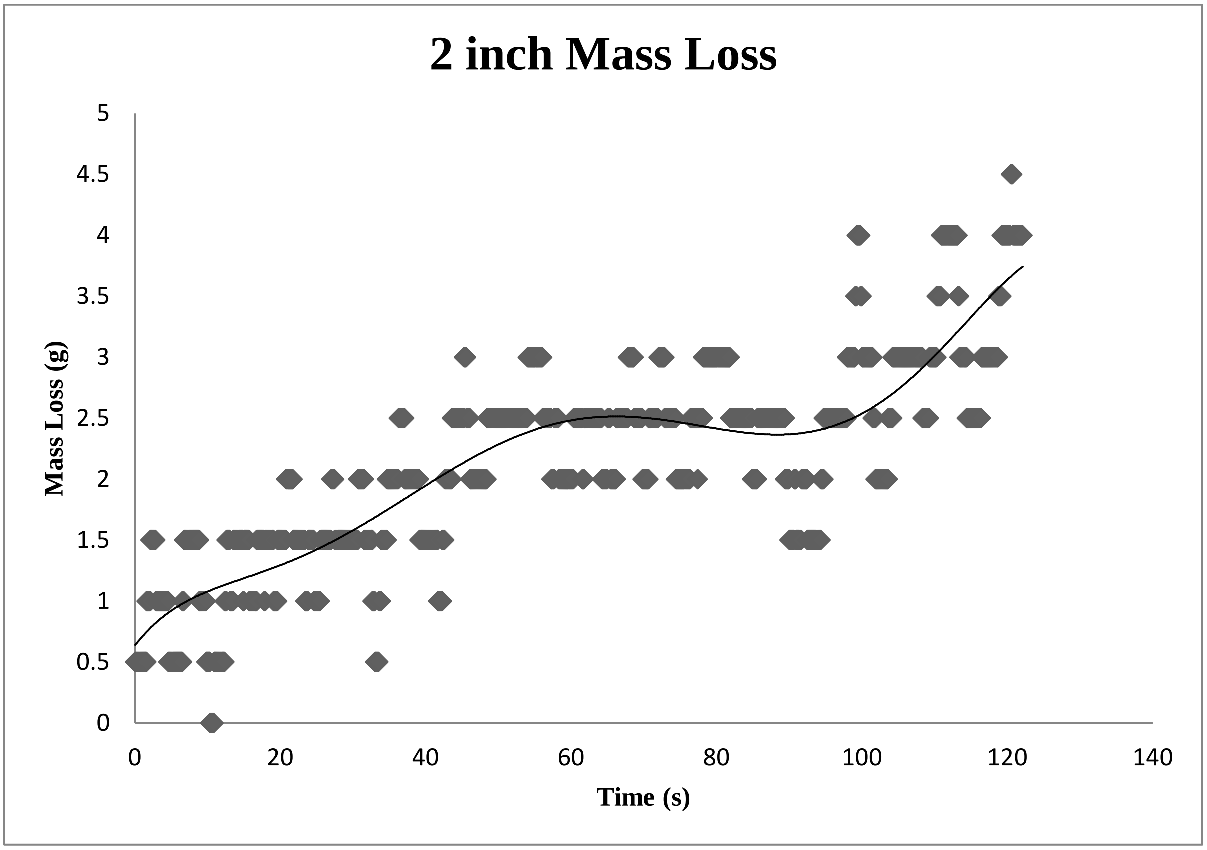


Figure 5: Mass loss of fuel in two inch inner diameter ice cylinders

The mass loss rate of fuel in each *in situ* burning was calculated by deriving the equation of dM with respect of t.

The plots showed that mass loss rate can be both positive and negative. It depends on whether the mass loss is significant with respect to time. As a function of time, mass loss rate may be negative when the mass loss is too small compare to the time has passed to loss the mass. The constant at the end of mass loss rate function served as an important factor of deciding the positive/negative sign. It came from mass loss function where t was at its first power. If the constant was greater than all the terms of t before it combined, mass loss rate would be positive.

Half-inch

$$\frac{dM}{dt} = -4.2 \times 10^{-12}t^5 + 2.5 \times 10^{-9}t^4 - 4 \times 10^{-7}t^3 + 3 \times 10^{-5}t^2 - 0.0004t + 0.0135$$

Figure 6: Mass loss rate of fuel in half inch inner diameter ice cylinders

One-inch

$$\frac{dM}{dt} = 1.2 \times 10^{-11}t^5 - 5 \times 10^{-9}t^4 + 4 \times 10^{-7}t^3 - 9 \times 10^{-6}t^2 - 0.0014t + 0.0501$$

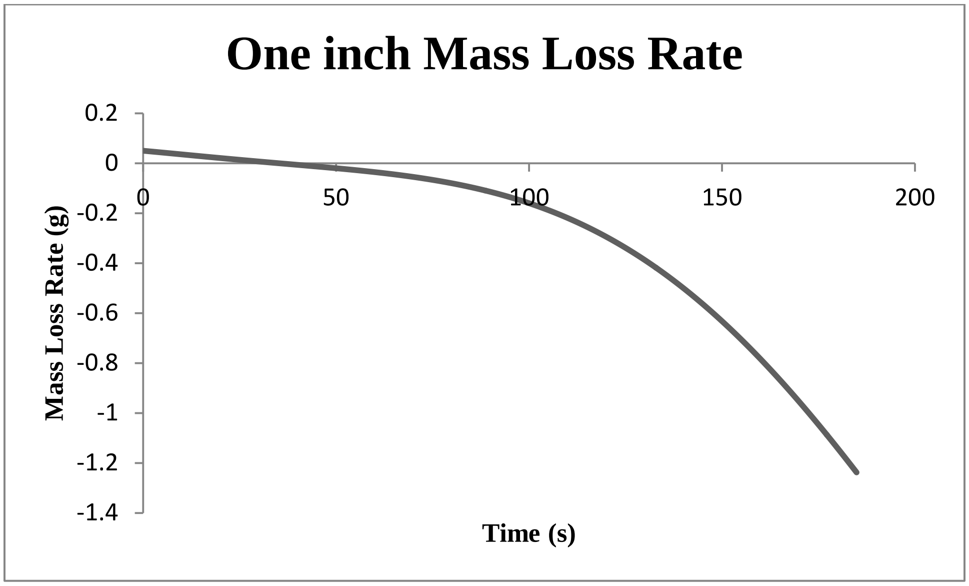


Figure 7: Mass loss rate of fuel in one inch inner diameter ice cylinders

One and half-inch

$$\frac{dM}{dt} = -1.2 \times 10^{-12}t^5 + 1 \times 10^{-9}t^4 - 3.2 \times 10^{-7}t^3 + 6 \times 10^{-5}t^2 - 0.0024t + 0.0442$$

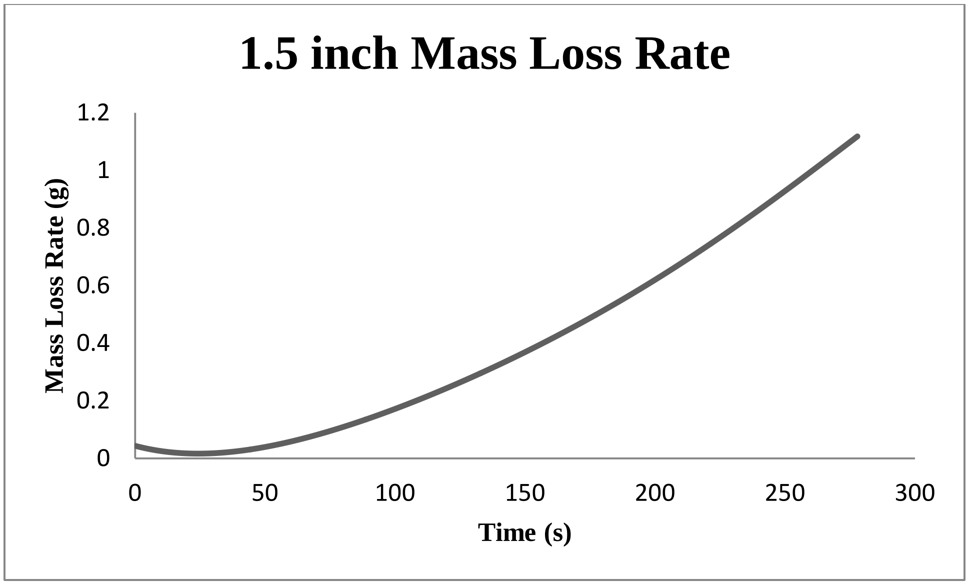


Figure 8: Mass loss rate of fuel in one and half inch inner diameter ice cylinders

Two-inch

$$\frac{dM}{dt} = -3.6 \times 10^{-10}t^5 + 1 \times 10^{-7}t^4 - 1.2 \times 10^{-5}t^3 + 0.0006t^2 - 0.0096t + 0.0769$$

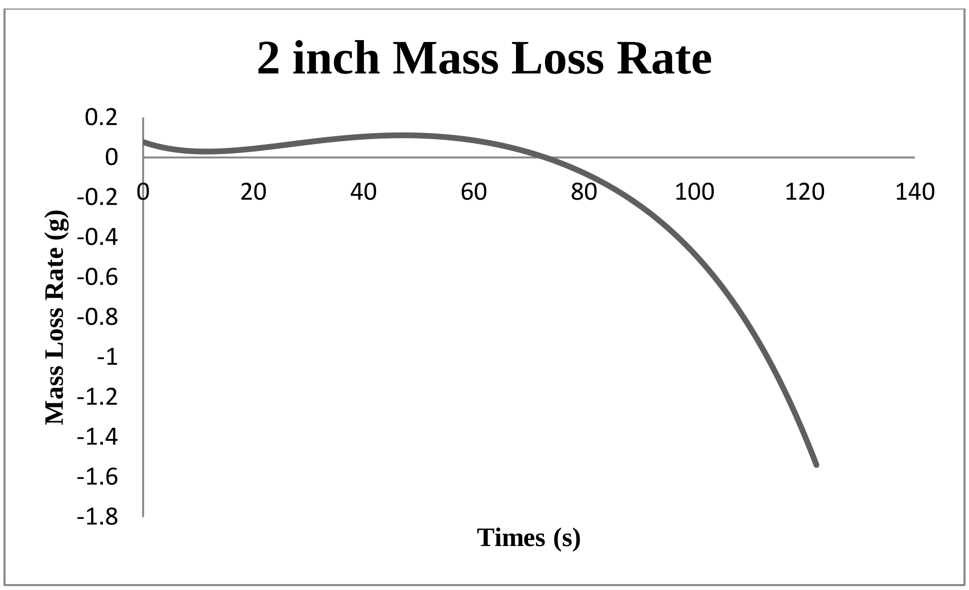


Figure 9: Mass loss rate of fuel in two inch inner diameter ice cylinders

Temperature Profile

During the burning test of a 2-inch inner diameter ice cavity, temperatures of fire in the center and temperatures in the ice wall as it melted were recorded and shown below. The purpose is to understand the heat changes inside the fuel/water layer and how the ice wall melted by the fire.

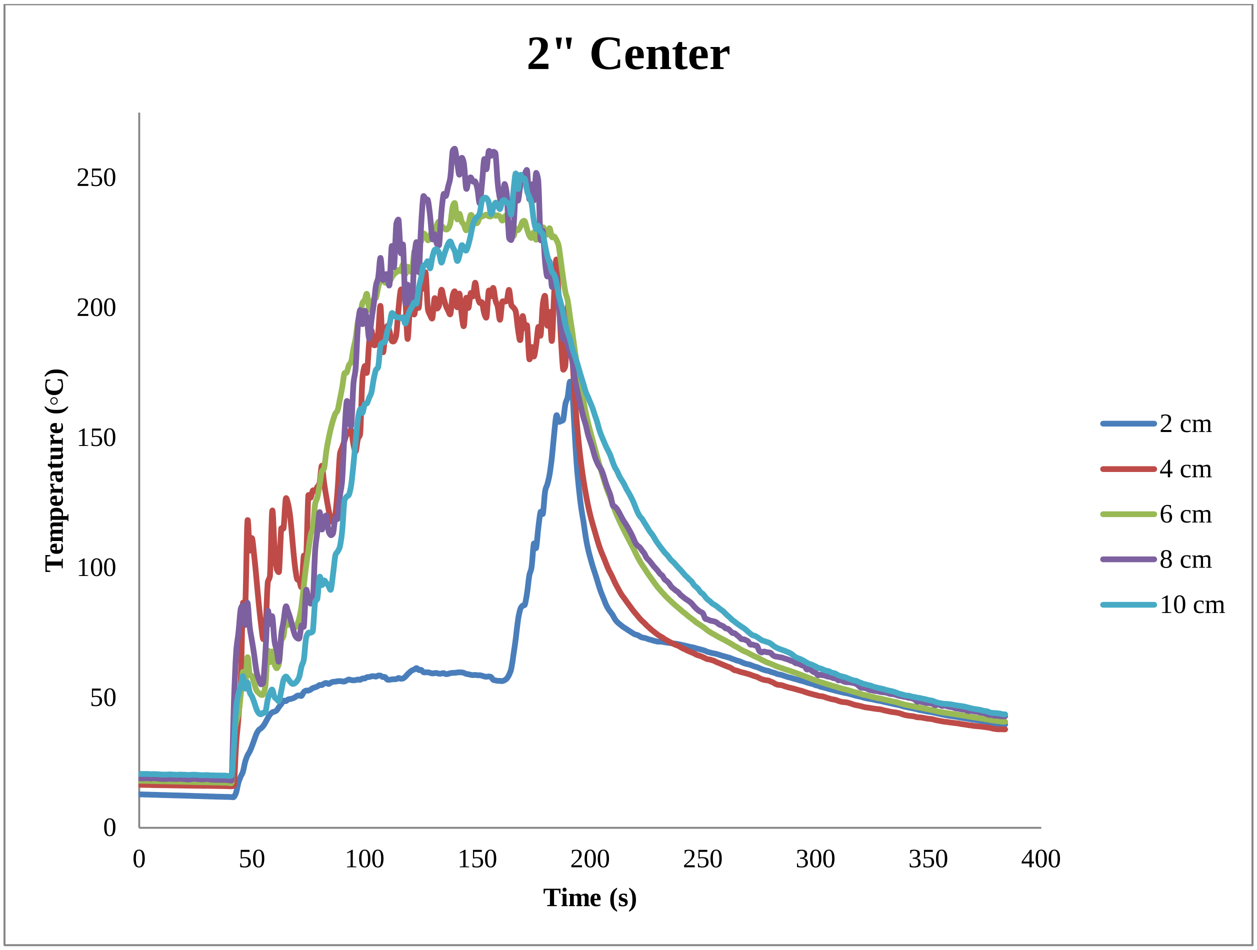


Figure 10: Temperature profile in the center of 2" ice cylinder

The dark blue line represents the temperature of fuel/water layer. After the ignition, liquids in the ice cavity started to quickly heat up, but stayed around 50-60 ◦C; reaching a heat balance with its surrounding ice. The balance was broken at 160 seconds when the fire was fully developed and reached its maximum heat release.

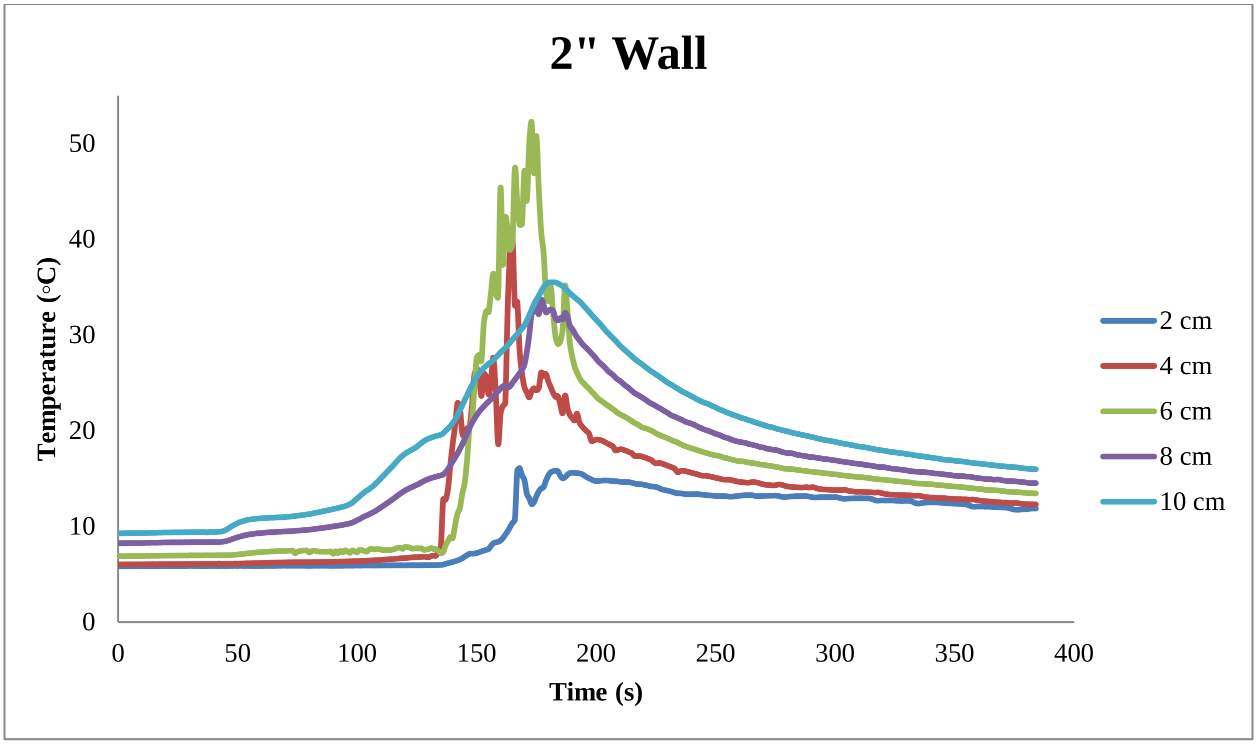


Figure 11: Temperature profile in the ice wall

As the fire started to melt the ice wall, thermocouples frozen inside got exposed to the heat. The first 140 seconds the ice was just melting. After the ice completely melted away, the thermocouples had direct contact with the flame, as shown in Figure 11 the sudden temperature increase after 150 seconds. The green line represents the temperature where it was 6 cm from the bottom of the ice cavity. It had the most exposure to the heat.

Overflow of 1-inch Inner Diameter Ice Cylinders

Overflow means there is enough fuel to release heat to melt the entire ice wall of the cylinder. In this experiment, 1-inch inner diameter ice cavities with 10 cm depth were chosen. 45 ml, 40 ml, and 35 ml fuel were burned. Tests had shown that 40 ml of the mixed fuel caused overflow with minimum fuel leftover.

If there was not enough fuel to cause overflow, two types of ice cylinders were found after the burn. One of which had a lip in the wall, as shown in Appendix 3. The other one had the lip at one moment, but was completely melted in the end, as shown in Appendix 4. Figure 12 shows the side view and dimensions of a 1-inch inner diameter ice cavity with lip when it was cut.

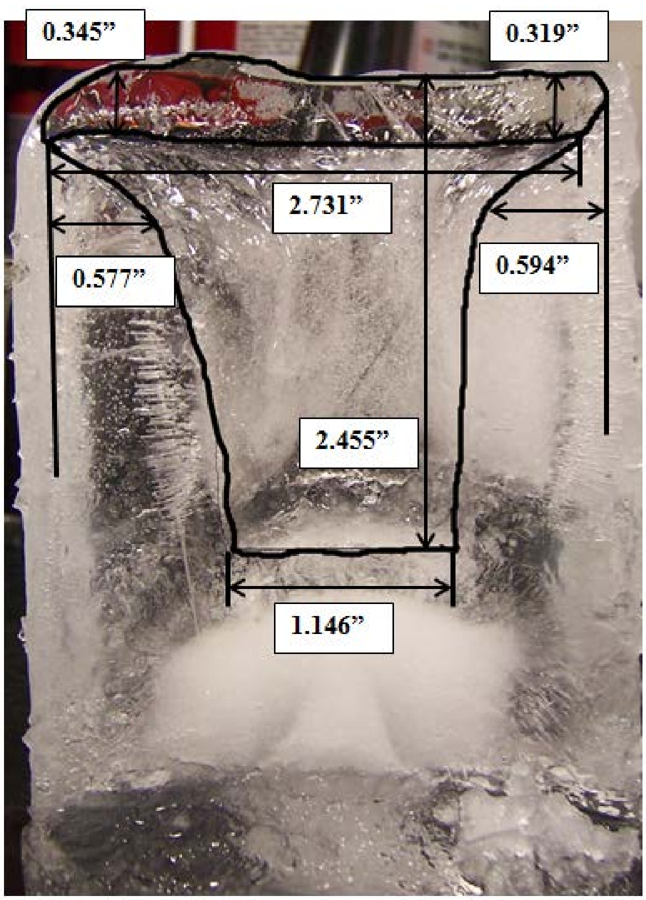


Figure 12: Measurements of an ice cavity with lip

Conclusion

A series of experiments were carried out to study the burning behavior of liquid fuel in ice cylinders. The studied aspects include fuel's mass loss rate can be both positive and negative; the temperature changes in the fire and in the ice wall are different in details but consistent in the general trend; and lastly it took 40 ml of fuel to make a 1-inch inner diameter ice cavity to overflow.

During the experiments, there were sometimes difficulties to ignite the fuel. A general observation was the ratio of cylinder inner diameter and cavity depth is influential for ignition. If the open surface is too small but the cavity is too deep, fire cannot sustain due to lack of oxygen and too much water vapor. Depth of the fuel layer can also be relevant. Future work is suggested to find out the exact factors that affected ignition.

References

Bellino, Peter W. *A Study of Spreading and In Situ Burning of Oil in an Ice Channel.* Master Thesis, Worcester: Worcester Polytechnic Institute, 2012.

BP Lubricants USA Inc. "466158-US12 US13, Castrol HD motor oil 30." August 20, 2010.

EMD Chemicals Inc. "PX0425 GR ACS petroleum ether." September 21, 2010.

Englund, Will, and Brad Plumer. "The Washington Post." *ExxonMobil signs Russian oil pact.* Washington, August 30, 2011.

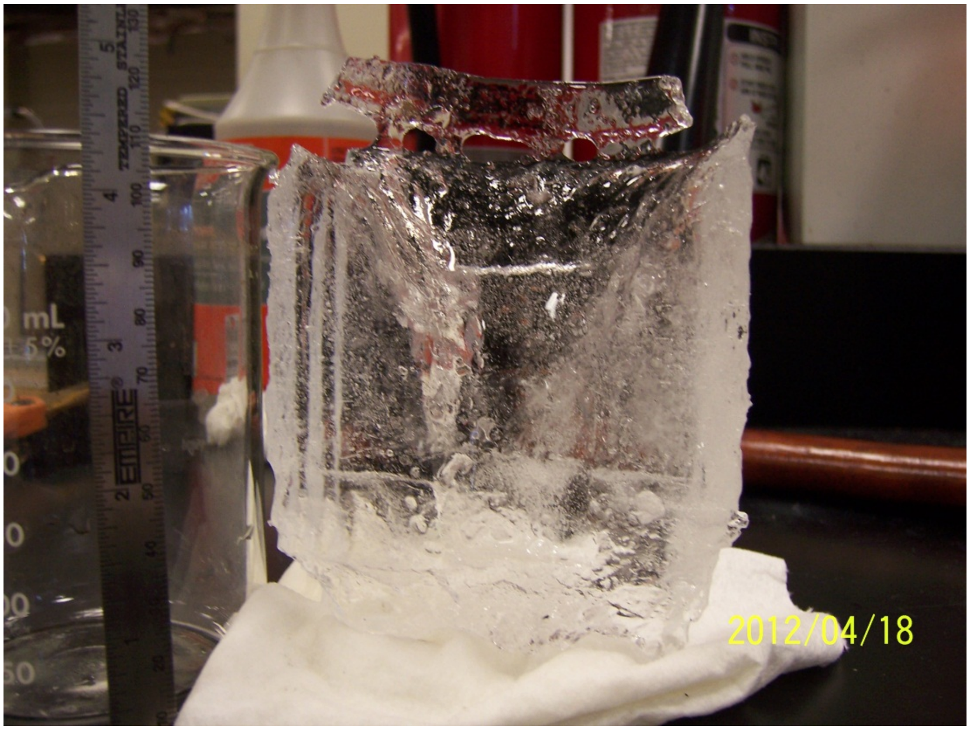
Murphy, Kim. "Oil drilling in Arctic nears reality: Shell emergency plan OKd ." Los Angeles Time, February 17, 2012.

Shell. *Shell Chukchi Sea Regional Exploration Program Oil Spill Response Plan.* Shell Gulf of Mexico Inc., 2011.

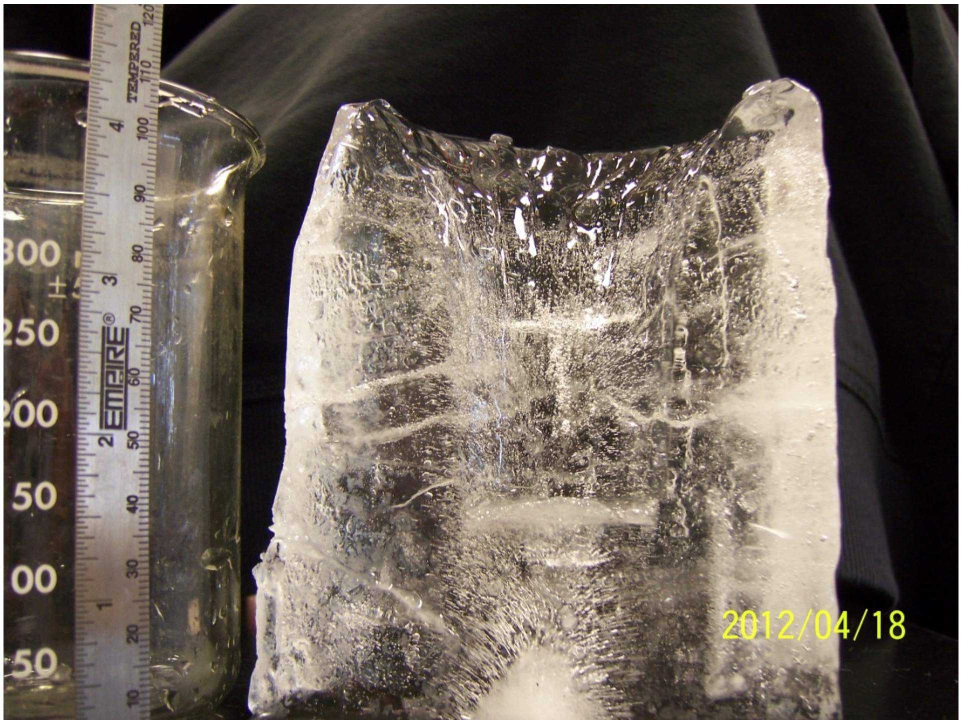
Appendix

Appendix 1: *In situ* burning of liquid fuel in an ice cylinder

Appendix 2: Over all experimental setup



Appendix 3: Non-overflow burning causing lip in the wall



Appendix 4: Non-overflow burning without lip in the wall