An Analysis of Oil Combustion on Snow

A Thesis

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Abstract

Several Arctic council reports conclude that oil spills are the most significant threat to the Arctic ecosystem. Some studies have shown that in-situ burning (ISB) of oil spills over water can remove more than 90% of the oil, and is the most promising technology for an efficient response to oil spills in the Arctic region. The definition of "In situ" is intentional, controlled burning of oil in place (i.e., without extracting or removing the oil first). Earlier studies [Bellino (WPI 2012), Farahani, (WPI 2014)] have investigated burning behavior of crude oil on ice, similar to what one would expect in sea-ice or bare lake ice conditions. The focus of the current study is to investigate the burning behavior of crude oil in snow, similar to oil spills in snow-covered land, or in snow covered sea ice in the Arctic. Understandably, due to the difference in packing density between ice/water and snow, the parameters that influence burning behavior of oil in snow are different compared to burning oil in the sea or ice conditions. The current experimental study shows that the snow behaves as a porous medium, and depending on the porosity and volume of the oil spill, two extreme behaviors are exhibited. In the case of an oil spill on snow with low porosity, the oil sinks easily to the bottom, and the burning involves, significant thermo capillary effects enabling the oil to rise up and burn. On the other hand, if the snow is less porous, most of the oil layer remains on the surface, approaching the case of an ice bed. However, the melting of snow due to flame heat flux causes a circulating flow pattern of the oil, whereby the hot layer at the surface moves down and comes back up due to capillary action. These processes, which have not been observed in the earlier studies, are physically explained in this study. The implications to overall efficiency of the burning process, which represents the amount of crude oil left in the snow after the burning process is discussed. The results will ultimately improve the strategies

and the net environmental benefit of, and by it the success of, oil clean-up after an accidental spill on snow.

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Chapter 1 Introduction

1.1 Motivation

There are several different marine activities that can lead to oil spills in the Arctic region, and the recently enhanced activity in the region is expected to increase the probability of an oil spill. Oil companies have spent over $600 million in the last two years in oil exploration in the Arctic [1] and Russia recently signed a $1 billion deal with Exxon Mobil for oil exploration in the Arctic [2]. After this deal, analysts predict the investment in oil exploration in the Arctic will reach more than $100 billion with many other countries (including the US) investing massive resources. However, as shown by the recent Deepwater Horizon accident, where oil goes spills follow. Figure 1 shows the yearly oil spill volume in gallons [3] which clearly proves that besides stricter regulations and safety measures to prevent oil spills, it is also important to invest in strategies to clean up oil spills efficiently.

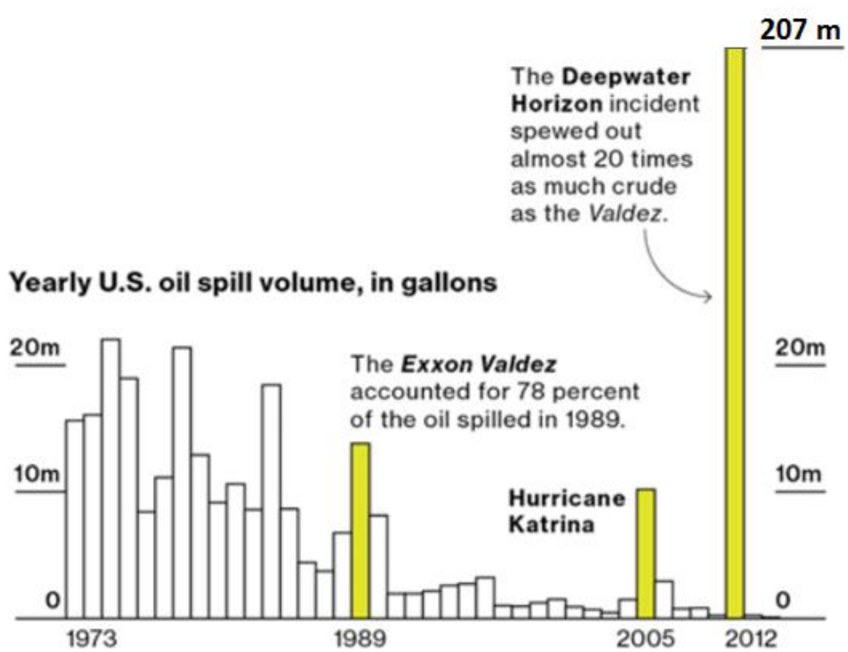

Figure 1: Yearly U.S. oil spill volume, in gallons [3].

If an oil spill were to occur under icy conditions in the Arctic [4], in-situ burning (ISB) defined as the intentional, controlled burning of oil in place (i.e., without picking up or removing the oil first) may be the only choice for efficient clean up, because the remoteness and harsh climate is likely to make it impossible for heavy machinery to be deployed immediately after a spill to facilitate either mechanical recovery or the use of dispersants, which are the two other primary response methods for offshore oil spill cleanup.

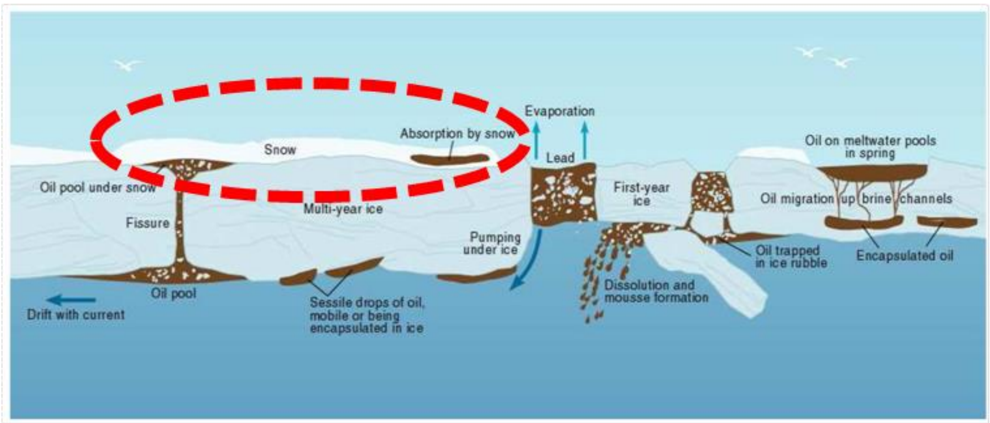

Figure 2: Possible oil/ice/snow interactions after a crude oil spill in the Arctic [5]. Circled area shows the focus of current study – oil spill on snow.

When it comes to oil spills in the Arctic, the presence of ice, ice channels, ice slurries and snow will cause changes in both the spread and burning behavior of the oil (Fig. 2). Earlier studies at WPI by Bellino (2012) and Farahani (2014) have investigated the burning dynamics of an oil spill on ice. The focus of this study is to investigate the burning of an oil spill on snow. This is indicated by the circled area in Fig. 2. It should be noted that the consequent environmental impact of an oil spill can be disastrous for the wildlife and ecosystems as well as for the indigenous people living in these areas [5]. The knowledge about the chemical composition of the residues from the in-situ burning and their toxicological impact on the Arctic environment, such as the wildlife and the underwater microorganisms, is also limited [6, 7]. ISB may be the simplest, quickest, and most efficient method to clean up an oil spill in the Arctic. However, engineering tools predicting ignition likelihood, flame spread, radiation, burning rate and burning efficiency are necessary to ensure protection of environment and workers during ISB. The proposed study is a step in this direction.

1.2 Previous related studies

There are several parameters that need to be investigated in order to fully analyze ISB on snow. In the Arctic, generally, ice will be covered with a layer of snow, which will absorb spilled oil as shown in Fig. 2. The oil spill then has to be ignited. Unlike an oil spill on solid ice or water, where a critical layer thickness (~0.5 mm) [8] is necessary for ignition, in the case of snow the oil absorption leads to a critical initial volume (compared to thickness). This further depends on porosity of snow and time. Finally, if the spill is ignited, the burning behavior of the crude oil in snow is also different compared to that on water [9] or ice [10, 11]. The literature review covers the three main aspects of oil spread in snow, oil ignition in snow, and oil burning dynamics in snow. Focus is given to burning dynamics as it forms the main objective of the current study and discussed in detail in section 1.3.

Oil movement in snow

The first parameter is to understand the rate of absorption or penetration of oil into snow which is mainly a function of the porosity of the snow. The study therefore involves the fluid dynamics associated with movement of a liquid in a porous medium [12, 13]. Kawamura *et al*. [14] carried out a series of experiments on the spreading of different chemicals, including mineral oils, in different types of snow, and correlated the results using Darcy's Law. Mackay *et al*. [15] performed on a series of small-scale laboratory experiments and larger field studies to understand the behavior of oil spilled on snow on terrain. Bech and Sveum [13] reported on a series of five large experiments each with 1 m^3 of diesel and crude oil released onto or under snow on sea ice. The most comprehensive study both summarizing the earlier experiments and presenting a model to represent the spread of oil in snow has been by Ross and Dickins [12], where an equation for a 2D horizontal spreading of oil in snow from an instantaneous release was reported.

Ignition of oil in snow

The second step is to understand the ignition behavior. In other words, what is the minimum ignition energy necessary to ignite the crude oil absorbed in the snow should be estimated. Based on the earlier researches reported in literature, there is no study that investigates this problem in fire or combustion literature. A good review of ignition in porous media such as an oil spill on a carpet, is available in Ma et al. [16]; however, the ignition mechanisms in snow have not been researched.

Burning behavior of oil in snow

The third and most important step, especially from a practical ISB - viewpoint is the burning behavior of crude oil in the snow. This aspect of the problem is the primary focus of the current study. McMinn [17] was one of the first to investigate the burning of oil absorbed in drifting snow. However, the first known parametric tests of oil burning in snow were reported by Energetex [18]. Burning process in small pits (100 x 50 x 10-cm^3) dug in an ice sheet involving pre-mixed blends of either fresh Prudhoe Bay crude or Arctic P40 diesel in snow has been reported. The snow content in the mixtures ranged from 55 to 83% by weight. Ambient temperatures were of the order of 0°C. Energetex also performed burning tests in small trenches (approximately 150 x 50 x 20-cm^3) cut in sea ice at McKinley Bay, NWT in the winter of 1979/80 with the same two oil types. The snow content of these mixtures ranged from 26 to 69% by weight. Air temperatures ranged from -31.5 °C to 3 °C. The results showed that the burning efficiency was around 70% which is about 20% lower than the burning efficiency usually observed in oil spills on open water [19]. A major finding was that the ambient air temperatures from -31.5 to +3°C did not appreciably affect the burns. However, the information collected still lacked one important parameter, namely the porosity of the snow. Sveum *et al.* [20] report on a series of experiments at Svalbard, Norway on burning oil in snow. In these tests, mixtures of snow and either diesel or fresh Oseberg crude were tested. In the small-scale tests (using about 8 litres of snow), unaided ignition was possible with up to between 25 and 50% snow by volume (approximately 16 and 23% snow by weight). Priming the mixture with fuel was necessary at higher snow contents. The efficiency was uniformly 90% or greater. The reason for the high efficiency was attributed to melting of the snow which released the oil for burning on top of the melt water in the test vessel. Little difference in the results for the two oils was noted. However, details of the snow porosity were not provided. Further it would be expected that the melting snow would also absorb significant energy from the flame and thus reduce the overall burning rate. However, this aspect was not discussed.

Summary and moving forward

A review of the prior literature, as discussed above, clearly shows that several parameters related to ISB on snow have not been fundamentally investigated in detail. When oil spills over snow, it behaves as a sponge and begins to absorb the oil. The transport of the oil, both vertically and horizontally, is a function of the porosity of snow and the surface texture of the snow. The consequent ignition and burning dynamics are complicated. The oil is dispersed in the snow either homogenously or non-homogeneously, depending on transport time and geometry. Upon heat transfer, the snow will melt resulting in change of porosity locally near the flame as well as near the hot burning oil. These parameters complicate the burning process which ultimately influences the burning efficiency. From a practical standpoint, the burning efficiency during ISB on snow should be optimized, and hence, the controlling parameters related to the burning of oil on snow should be clearly understood. The primary objective of this study is a step in this direction.

1.3 Objectives of the current study

With the status of the previous literature in mind, the present investigation is intend to extend the fundamental understanding of oil burning dynamics of oil burning in snow. The specific objectives are as follow:

1. A small scale experimental setup is to be designed, constructed and instrumented to investigate the impact of snow porosity on the burning dynamics of an oil spill in snow.
2. The initial spill volume, or in other words the oil to snow ratio, is an important parameter and investigated earlier by other researchers. Two types of experiments with oil to snow

volumetric ratio as 1:1 and 0.5:1are planned to investigate the impact of this parameter on the burning behavior. These experiments also allow comparison of the present results with that from the past work.

3. Experimental data in the form of mass loss rate, temperature profiles as a function of height of the snow layer, and flame photographs, are used to further explain the burning dynamics.
4. Both laminar and turbulent flow conditions are investigated by varying the diameter of the apparatus in the range of 5 cm to 15 cm.

To explain the results contributing to the above-mentioned objectives, the thesis is organized in four Chapters: Introduction, Experimental setup, Experimental Results and Analysis, and Conclusions and Future work. An Appendix is also included at the end of this thesis, to provide additional details related to setup, experimental data analysis, and photographs.

Chapter 2 Experiment Setup and Procedure

2.1 Design and construction of experimental test apparatus

Figure 3 shows the experimental setup built to investigate burning dynamics of oil on snow. The setup comprises of an inner and outer concentric cylindrical metallic containers. The outer container has 2 times the diameter of the inner container. Three different configurations were made such that the inner diameter of the vessel containing the snow-cavity could be varied as 5, 10 and 15 cm, with corresponding outer container diameters of 10, 20, and 30 cm. The height of all containers was kept as 5 cm. Figure 3 shows the setup for the 5 cm diameter case. Water was poured in the inner and outer containers and frozen in a freezer such that the entire outer container and the half of the inner container contained solid ice as shown in Fig. 3.

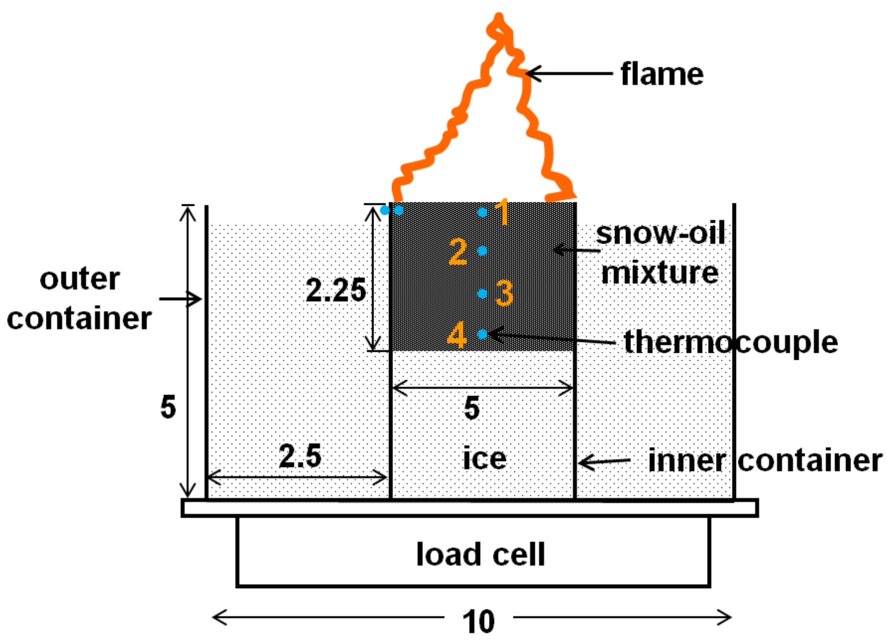

Figure 3: Experimental setup (dimensions in cm.)

The cavity in the inner cylinder (2.5 cm × 5 cm as shown in Fig. 3) was then filled with snow. Two packing densities of 0.5 g/mL and 0.7 g/mL were used, thereby creating a snow cavity of two different porosities. The set up was then placed on a load cell and the initial mass is recorded. A known volume of oil, which comprised of a 3:1 mixture SAE 30 motor and petroleum ether, similar to that used by Bellino (2012), was then poured slowly over the snow cavity. After waiting for 10 minutes, the oil was ignited. In addition to mass loss data, four thermocouples (indicated by 1 - 4 in Fig. 3) were used to obtain the in-depth temperature profiles as a function of time during the burning process. The centerline thermocouple tree comprised of 4 K-type thermocouples (0.125 cm diameter, spaced 0.62 cm apart) to measure the temperature of the oil layer and the oil and snow mixture. The bottom thermocouple labeled "4" in Fig. 3 was placed 0.25 cm from the lower ice wall. Two additional thermocouples were placed on the inner and the outer shells of the inner container to estimate the lateral heat losses during the experiment. A video camera is used to record the burning behavior and to measure the visible flame height. A 3-sided enclosure shield is placed around the setup to ensure that the flow field during the experimental burn was not influenced by random drafts in the laboratory. This was especially necessary for the small laminar flames established during the combustion of 5 cm snow cavity.

The initial volume of the oil was chosen to ensure that ignition was always possible using a small butane torch-igniter held over the vessel for 5 s or less. Given the type of oil used and also based on earlier studies discussed in section 1.2, a value of 1:1 and 0.5:1 for oil to snow ratio was decided. Several trials were performed to arrive at 0.5:1 limit. It was found that especially for the small diameter (5 cm) and low packing density cases, going below the 50% oil to snow mass ratio resulted in prohibitively longer ignition times. Due to this reason, 50% was chosen as the lower cut-off value. It should be noted that this value is comparable to the 30% - 40% oil to snow ratio, as reported by Buist etl al. [21].

Several preliminary trials were also performed to arrive at the snow packing density. A “high–packed” condition was obtained at 0.7 g/mL whereby only a small portion of the oil could penetrate into the snow. Thus the inner container could be filled (although very slowly) to the desired oil to snow ratio without spilling the oil out into the outer container. Any increase beyond 0.7 g/ml did not allow pouring all the required amount of oil without spilling in to the outer container. A value of 0.5 g/ml snow packing density was chosen to be the “low –packed” value. As discussed earlier this value was chosen based on ease of ignition. This was the minimum quantity at which the oil could be ignited by the small butane torch within 5 s.

2.2 Experimental matrix

Figure 4 shows the experimental matrix chosen for the current study. With three different diameters, two values of snow packing density, and two values of weight ratio, 12 different experiments have been performed. Each experiment has been repeated three times to form a total set of 36 experiments. In all the experiments, fresh oil-snow mixtures were prepared and the ice in the outer container was also replaced.

2.3 Oil type

Owing to difficulty in obtaining crude oil, it was necessary to create an oil solution that would simulate crude oil. The oil solution utilized was a mixture of SAE 30 motor oil and petroleum ether in a proportion of 3:1. The proportion was arrived at by performing an experiment using 75 ml of SAE 30 motor oil with increasing amounts of petroleum ether in a stainless steel pan of diameter 5 cm. The ratio of 3:1 SAE 30 oil to petroleum ether achieved a successful 100% burn efficiency leaving no oil remaining in the pan. Table 1 shows the property of the oil mixture [Bellino, 2012.]

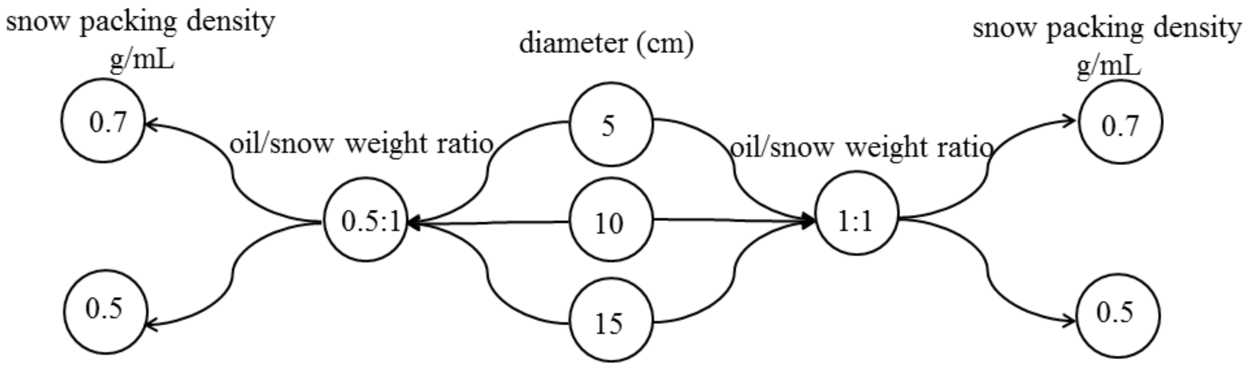

Figure 4: Experimental matrix.

	Oil Mixture*	Crude Oil**
Liquid Density (kg/m^3)	884	866
Viscosity (centi-poise, cP) @ 25°C	11.04	11.04
Flashpoint (°C)	161C	25-35
Boiling Point (°C)	236 C	38-570
Thermal Conductivity k (W/m.K)	0.142	0.09-0.14
Specific Heat, Cp (kJ/kg.K)	1.91	2.2
Latent Heat L_v (kJ/kg)	250	250

Table 1: Properties of Oil Mixture and Alaska North Slope Crude Oil at 25°C [Bellino, 2012*, Rangwala et al. 2013]**

Table 1 shows the properties of motor oil to petroleum ether mixture compared to Alaska North Slope crude oil. This comparison shows the similarities in the relevant physical properties of the mixture and the crude oil. With the conducted experiments to obtain a complete combustion and the shown physical properties it was confirmed that 3:1 motor oil to petroleum ether mixture can simulate the crude oil.

Chapter 3 Results and Analysis

3.1 Estimation of mass burning rate

The mass loss rate plays a significant role for ISB and it is directly related to the burning efficiency. Low mass loss rate indicates lower burning efficiency. Understanding the factors those affect the mass loss rate will aid in determining if the ISB would an effective option under the given set of conditions. Different critical parameters have been discussed that can have a major impact on the mass loss rate.

As previously mentioned there were three different containers with different physical parameters were ignited and the corresponding burning behavior of oil was analyzed. Figure 5 shows the mass-loss data collected from the load cell plotted as function of time for the 5 cm diameter case. For this particular trial, the oil to snow weight ratio is 1:1 and the snow packing density is 0.7 g/ml. Three experimental trials are performed and the average mass loss vs. time is shown by the solid line. The three trials are showing in Fig 5 every 10 seconds to clearly illustrate the data points on the graph. The error is estimated between these trials is to be on the order of ±0.05 g/s. For all the experiments, measurements of mass loss over time have been taken at a time interval of 0.2 s. A third, fourth, or fifth polynomial is fitted to the data, assuring that R^2 value is not less than 0.9. For example, in Fig. 5, the dark solid curve is represented by a 3rd order polynomial fit which was used to fit the data. The equation for mass over time is shown in equation (3.1.)

$$\mathbf{dM = -2 \times 10^{-08}t^3 + 2 \times 10^{-05}t^2 - 0.0128t + 17.018} \qquad \mathbf{(3.1)}$$

The mass-loss rate was calculated by differentiating this polynomial giving the following equation:

$$\mathbf{dM/dt = (3 \times -2 \times 10^{-08} t^{2}) + (2 \times 2 \times 10^{-05} t) - (0.0128)} \qquad \mathbf{(3.2)}$$

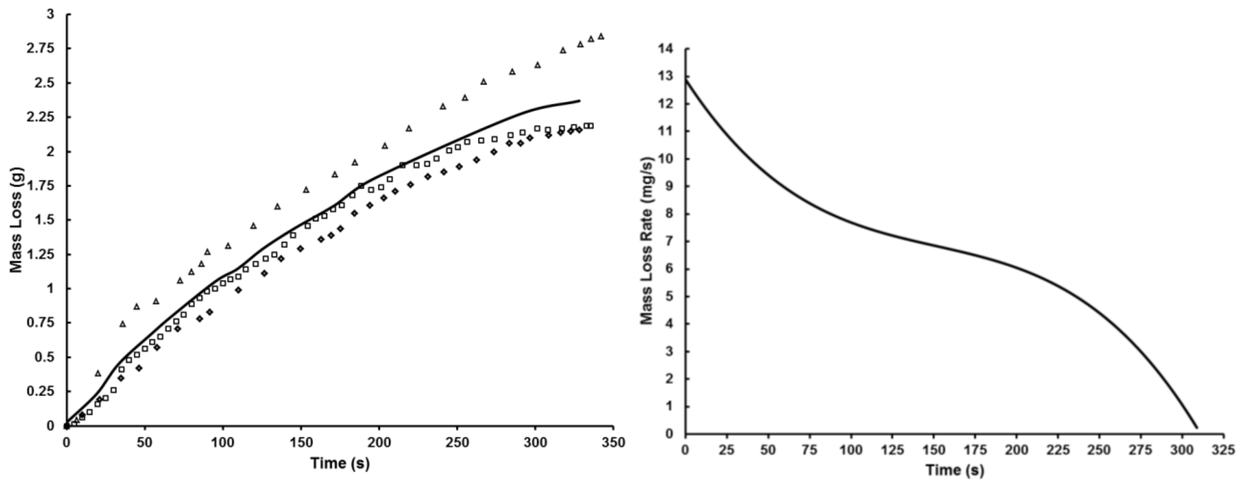

Figure 5: **The left figure shows raw data for the 5 cm container with the three trials shown with a 3rd-order polynomial trend line on the average mass loss. The error is to be on the order of ±0.05 g/s. The figure on the right shows the calculated mass-loss rate from the derivatives of polynomial fits of recorded mass lose over time**

The mass loss rate vs. time on Fig. 5 on the right hand side shows the mass loss rate is high initially started high and decreased with time as this behavior makes sense, since the oil is floating on top of the vessel when ignited. Hence, the oil on top surface is burning and not yet penetrated into the snow. As time progressed, the oil started to distributed and penetrated within the snow and hence the oil was no longer combust.

A similar procedure was used for all experiments performed and all mass loss and mass loss rate curves are shown in appendix A. The mass loss rate data along with temperature profiles are used to understand the burning dynamics of the oil absorbed by snow. During each trial, two effects coalesced to affect the mass loss rate as the flame continued to melt the snow layer. The first is the increase in the surface area of the fuel and the second is the decrease in the ullage height. The mass loss rate is recorded from the time when a self-sustaining flame is visible through extinction and the effects of the ignition period are ignored.

3.2 Role of diameter, packing density and initial volume on mass burning rate

The experimental burning rate is shown in Fig. 6. Note that each curve is an average of three repeated experimental trials. The burning rate increases as the diameter of the snow-oil mixture increases as shown in Fig. 6. The oil/snow ratio seems to have a significant influence on both the duration and maximum or peak value. In Fig. 6a and b, where the oil/snow ratio equals 1:1, the peak burning rate is close to 75 – 80 mg/s (D = 15 cm), whereas it is 45 – 65 mg/s (D = 15 cm) for the oil/snow ratio is 0.5:1.

The duration of the burn is also lesser; for D = 15 cm case, the burn lasts for ~400 s for the higher oil/snow ratio and it only lasts for ~250 s for the lower oil/snow ratio. This is due to the lower volume of oil in the latter. It is interesting to note that the trend or initial and final slopes of the curves are also remarkably different as dictated by the flame dynamics.

For low oil/snow ratios (Fig. 6c and 6d), the burning rate is initially low. It then increases rapidly to a peak value after which it declines. On the other hand, for the high oil/snow ratios (Fig. 6a and 6b), the initial mass burning rate is higher, it further increases and then declines. Similar trends are also observed for the D = 10 cm and D = 5 cm diameters.

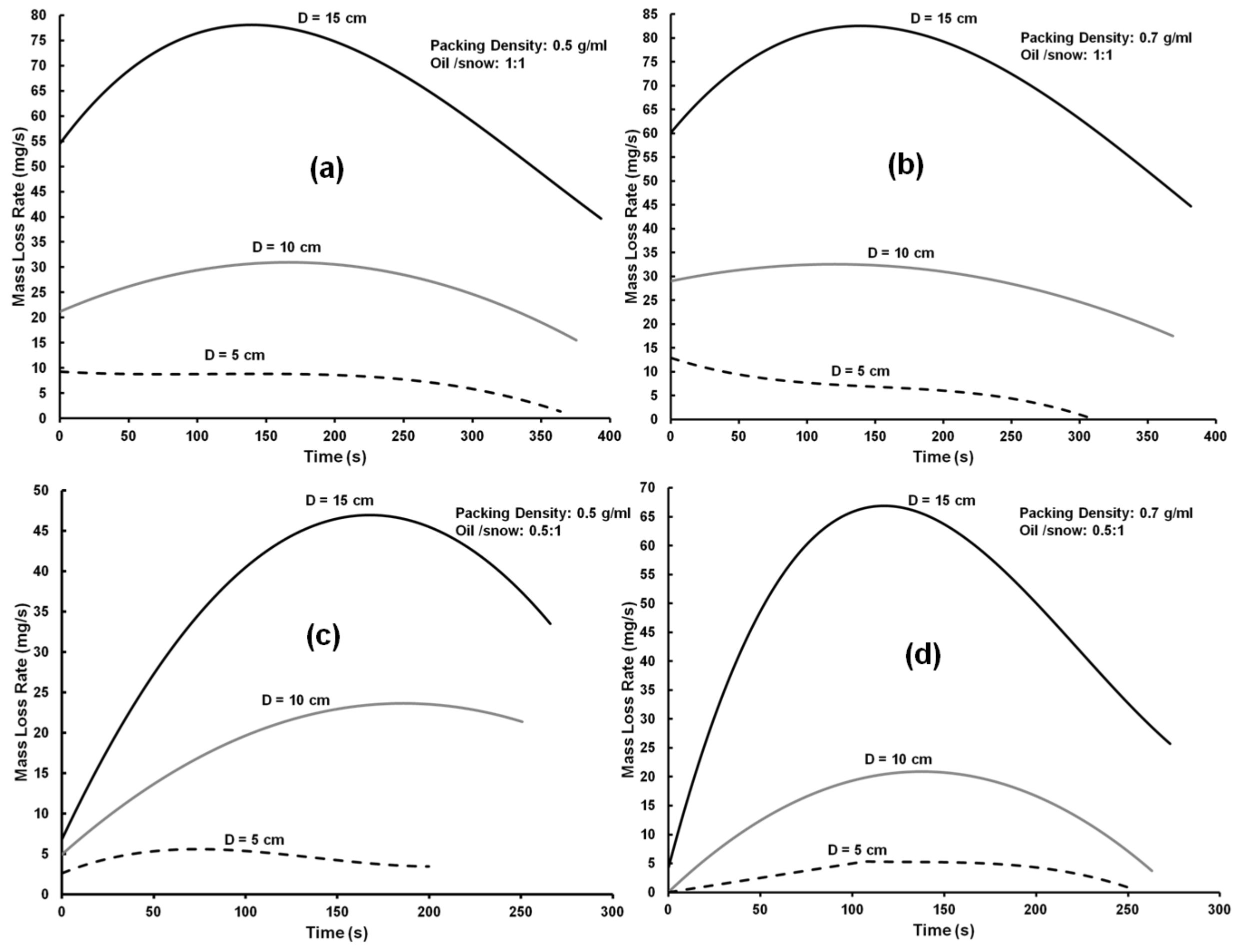

Figure 6: Experimentally observed burning behavior. (a) Packing density = 0.5 g/ml and oil/snow = 1:1, (b) Packing density = 0.7 g/ml and oil/snow = 1:1, (c) Packing density = 0.5 g/ml and oil/snow = 0.5:1 and (d) Packing density = 0.5 g/ml and oil/snow = 0.5:1.

Two packing densities are used in this study. In the lower packing density equal to 0.5 g/ml, the snow is highly porous and the poured oil tends to sink down rapidly thereby creating a concentration gradient in oil, lower to higher, from top to bottom. The high packing density of 0.7 g/ml is high enough to cause the oil to form a layer above the snow surface, because the porosity of the snow makes it difficult for the oil to penetrate. In this case, it was observed that the oil moved laterally to sideways almost at the same rate. The final concentration profile of the oil in the snow was high to low from top to bottom, which is an opposite trend in comparison with the low packing density case.

The influence of packing density on the burning behavior can be observed by comparing Fig. 6a and 6b, where equal oil/snow ratios are used with different packing densities. In Fig. 6a, the packing density is 0.5 g/ml and in Fig. 6b the packing density is 0.7 g/ml. As the packing density increases, it is observed that both the initial and peak mass burning rate increase by around 10% for all diameters. This is attributed to the differences in the initial concentration profiles of the oil in snow for the two packing densities. The presence of higher amount of oil at the surface in the high packing density case, leads to enhanced burning. However, there is no significant change observed in the variation trends, except for the 5 cm diameter case; a monotonic decrease is observed in the high packing density case, and more steady regime is observed in the low packing density case for longer time, due to interaction of melted water and oil.

The oil/snow ratio in Fig. 6c and 6d is 0.5:1. There is less oil per unit volume in these cases. Due to this, the mass loss rate is much lower in these cases when compared to that in the cases with oil-snow ratio of 1:1. Figure 6c shows the low-packed case (0.5 g/ml) and Fig. 6d shows the highly packed case (0.7 g/ml). It is apparent that the mass loss rate increases with increasing diameter; for the larger diameter (D=15 cm), a significant increase of ~45% in mass burning rate occurs in the high packing density case. However, the effect of packing density has all-together different trend in these lower oil-snow ratio cases. First of all, the initial mass loss rate has been higher for higher packing density in the case of oil-snow ratio of 1:1, but in this case (0.5:1), the initial mass loss rate is higher for lower packing density case; it is apparent that for lower D values, the initial mass loss rate starts from nearly zero. Second, the trend in the time of burning is also reversed; for 1:1 ratio, low packing density cases burn for slightly longer time and for 0.5:1 ratio, high packing density cases burns for slightly longer time. The reasons for the significant increase in the peak value of mass loss rate for the larger diameter case with high packing density is explained further in Section 3.3.

It is also obvious from Fig. 6 that both parameters, packing density and initial oil/snow ratio are coupled, and it is difficult to separately appreciate the effect of one parameter without accounting for the effect of the other. This is evident when comparing Fig. 6a and 6d. Although the initial mass loss rate is low for Fig. 6d due to low initial oil volume, the high packing density causes the oil at the surface to warm up quickly and results in a high mass burning rate. The initial burning rate increases significantly from 5 mg/s to around 65 mg/s in 150 s representing approximately a 1200 % increase! The burning of a thin layer of oil, without much snow, on a cold substrate, is a rapid process. Initially, the burning-rate is very low, which is due to the effect of the cold substrate that necessitates more sensible heat to be supplied to the thin cold oil layer. As the oil burns and melts the surrounding snow to liquid water, the heat transfer to the condensed phase is restricted to the supply of energy for phase change alone, and hence the burning rate increases dramatically. Of course, this rapid burning process continues only for some time, till the oil-layer is able to maintain a critical thickness (observed as ~3 mm – 5 mm).

On the other hand, in Fig. 6a, the oil tends to sink down due to low packing density. However, due to the higher oil/snow ratio, the oil concentration throughout the snow is almost uniform. The oil-snow system behaves as a cold porous wick saturated with oil. Therefore, in this case, the burning rate does not increase as dramatically as in Fig. 6d, even though the burning rate is much higher right from the beginning. The case in Fig. 6(a) is controlled predominantly by mass transfer from a effective two-component system (oil and snow), mixed quite well, and that in Fig. 6(d) is controlled predominantly by coupled heat and mass transfer to an almost single component oil system. The initial mass burning rate increases from 55 mg/s to 75 mg/s in 150 s showing an increase of around 36%. This is significantly lower than the value of 1200% observed in Fig. 6d. It is further noted that the rate of decrease of the mass burning rate (from 65 mg/s to 25 mg/s in approximately 125 s) is more than double of the case in Fig. 6(a) (mass burning rate decreases from 75 mg/s to around 40 mg/s in around 250 s). This is attributed to the lower oil content in the case in Fig. 6(d). The significantly unsteady burning process in the case of Fig. 6(d) requires more time to consume lesser amount of oil than that in Fig. 6(a), where the burning rate is notably steadier.

3.3 Temperature profiles

Figures 7-9 show the in-depth temperature profiles obtained using TC's 1-4 shown in Fig. 3. "A" represents oil/snow ratio of 0.5:1, and packing density = 0.5 g/ml, "B" represents oil/snow ratio of 1:1, and packing density = 0.7 g/ml, "C" represents oil/snow ratio of 0.5:1, and packing density = 0.7 g/ml, and "D" represents oil/snow ratio of 1:1, and packing density = 0.5 g/ml. Figure 7 shows the temperature profiles for the 5 cm diameter case. The relatively high spike for A in the TC located at the surface is because of the butane torch that had to be held for a longer time to ignite this case. The burning in case B and C occurs at a high packing density. As discussed earlier, in this case, the oil preferentially stays on the surface due to the low porosity of the snow. Due to this reason, the burning proceeds such that the top layer which is oil rich burns as a thin slick. Correspondingly the temperature recorded by TC 1 is equal or greater than the boiling point of the oil (~230 – 270ºC). In both B and C cases a hot oil layer is formed between TC 1 and 2 which sustains a steady burning. As the snow melts, the burning rate enhances to some extent, which is observed by the gradual increase in the temperature of TC 2.

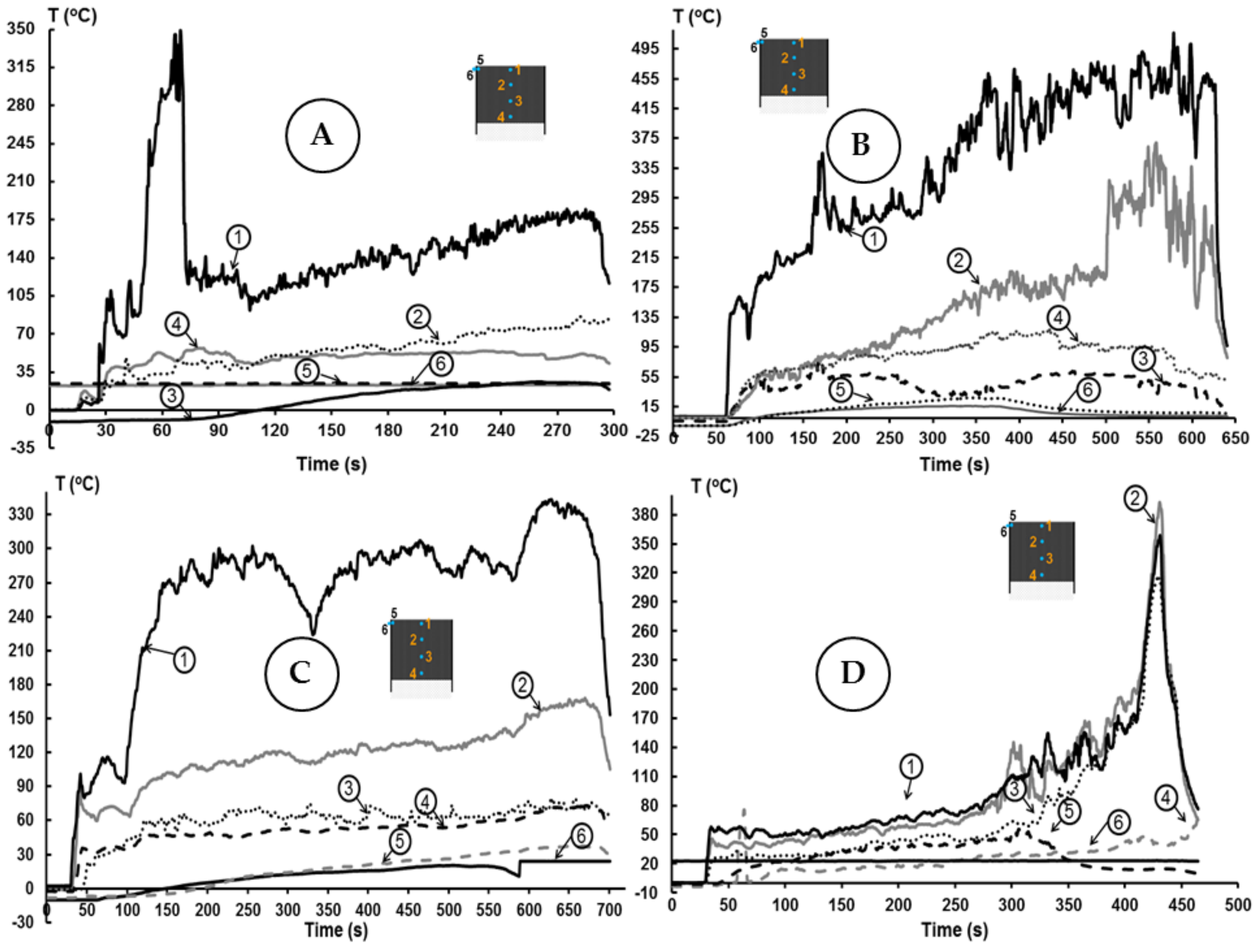

Figure 7: Temperature data for 5 cm container; (A) weight ratio is 50% and snow packing density is 0.5 g/ml (B) weight ratio is 100% and snow packing density is 0.7 g/ml (C) weight ratio is 50% and snow packing density is 0.7 g/ml (D) weight ratio is 100% and snow packing density is 0.5 g/ml

It is also interesting to note that the temperature at the bottom (TC4) supersedes that of TC3 for B and is almost the same as TC 3 for C. This proves that warm oil-water mixture accumulates at the base of the container during the combustion. Since both B and C have high packing densities, the movement of the oil/liquid water is mainly through the sides, where a cavity is formed due to melting of snow because of heat conduction from outer metallic rim. This effect is further explained in Section 3.4.

Figures 7A and 7D are for the cases with low snow packing densities. In Fig. 7D, the oil/snow ratio is high (1:1). In this case, the snow behaves as a sponge absorbing the oil such that the concentration of the oil is uniform throughout prior to ignition. No thin upper layers like discussed in Fig. 7B and 7C are observed. It is due to this reason, that all the in-depth temperature profiles are fairly close to each other, with TC1 being the highest because it is located closest to the flame and progressively decaying down from TC 1 to TC 4. For 1:1 ratio and low snow packing, the uniformity in the oil concentration is so high that all the thermocouples record almost similar temperatures for most of the combustion period. This approaches the burning of an oil water emulsion that is uniformly mixed. Towards the end, when sufficient snow has melted, a thin oil layer is formed at the surface. However, this phase is short-lived (~30s) and rapid extinction is observed, once the snow melts to an extent that the oil concentration is not enough nor homogenous.

In the case shown in Fig. 7A, the burning is mainly due to the formation of a small crater that's formed due to melted snow during ignition and the consequent expansion of this crater. This is further explained in Section 3.4.

For the larger diameter cases, shown in Figs. 8 and 9, similar trends are observed, however, with a different time durations and fluctuations.

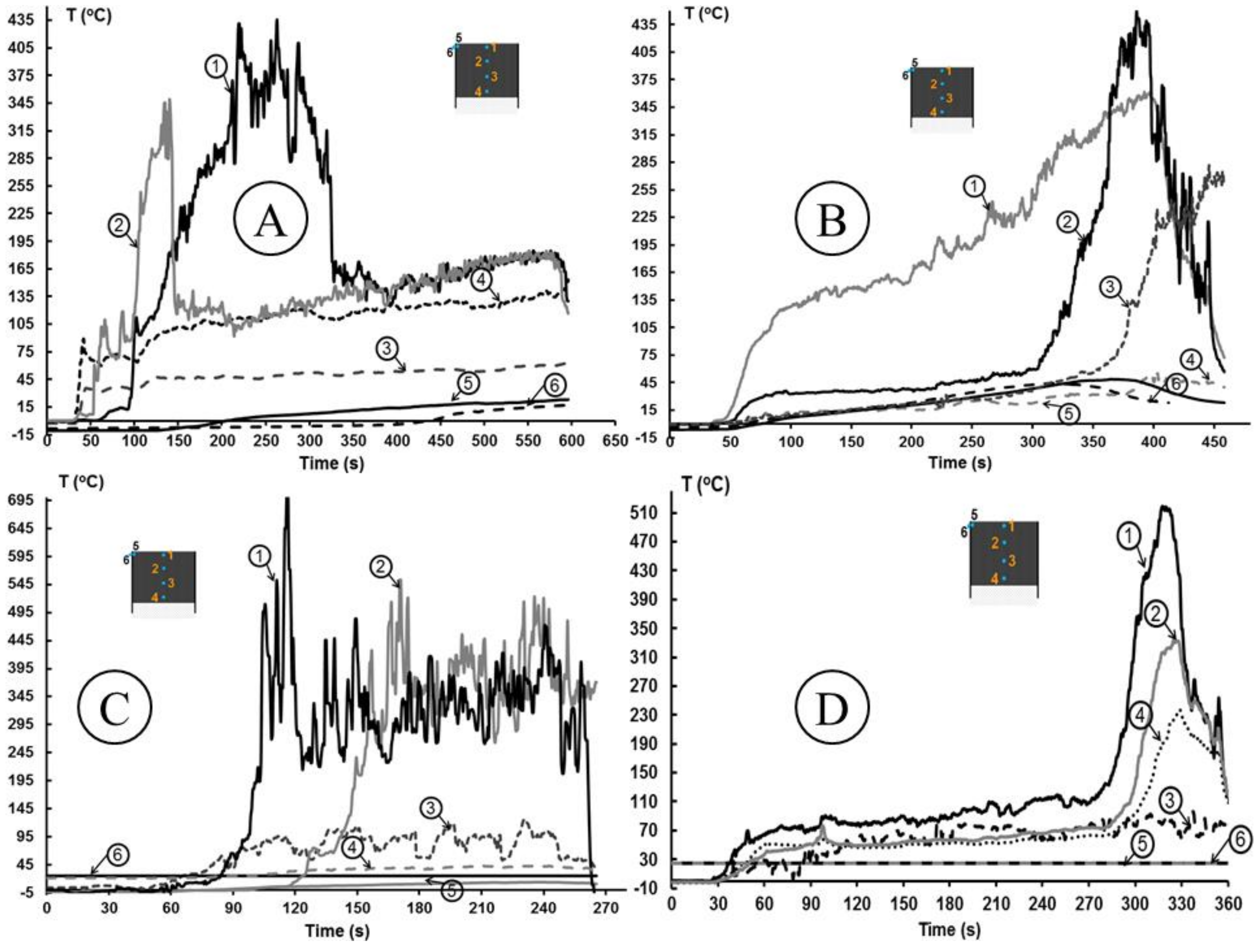

Figure 8: Temperature data for 10 cm container; (A) weight ratio is 50% and snow packing density is 0.5 g/mL (B) weight ratio is 100% and snow packing density is 0.7 g/mL (C) weight ratio is 50% and snow packing density is 0.7 g/mL (D) weight ratio is 100% and snow packing density is 0.5 g/mL

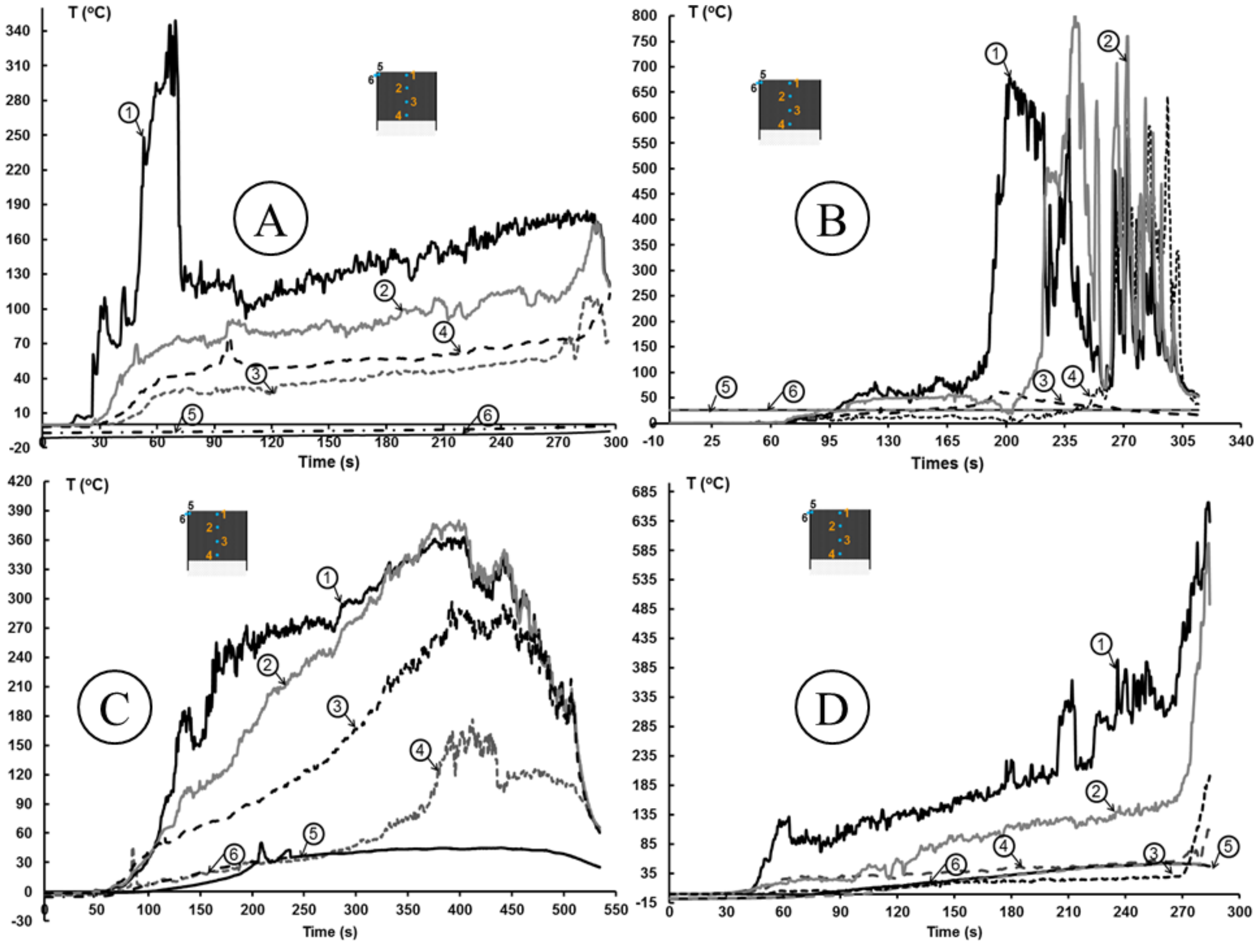

Figure 9: Temperature data for 15 cm container; (A) weight ratio is 50% and snow packing density is 0.5 g/mL (B) weight ratio is 100% and snow packing density is 0.7 g/mL (C) weight ratio is 50% and snow packing density is 0.7 g/mL (D) weight ratio is 100% and snow packing density is 0.5 g/mL

3.4 Description of the burning dynamics of oil on snow

Figure 10 shows the burning efficiency for different snow packing densities (0.5 and 0.7 g/ml) and oil to snow ratios (0.5:1 and 1:1). Burning efficiency is defined as mass burnt/initial mass of the oil, and is expressed as a percentage. Once the experiment arrived at its extinction phase, the mass of oil is then subtracted from its initial mass which gave the mass the oil that has been burnt. Hence, the mass of oil burnt as explained was then divided over the initial mass and the resulting value was multiplied by 100 to get the burning efficiency. Each vertical bar is an average of 3 experimental trials. In each case (a – d), the three bars denote the efficiency at the three different diameters of 5, 10 and 15 cm.

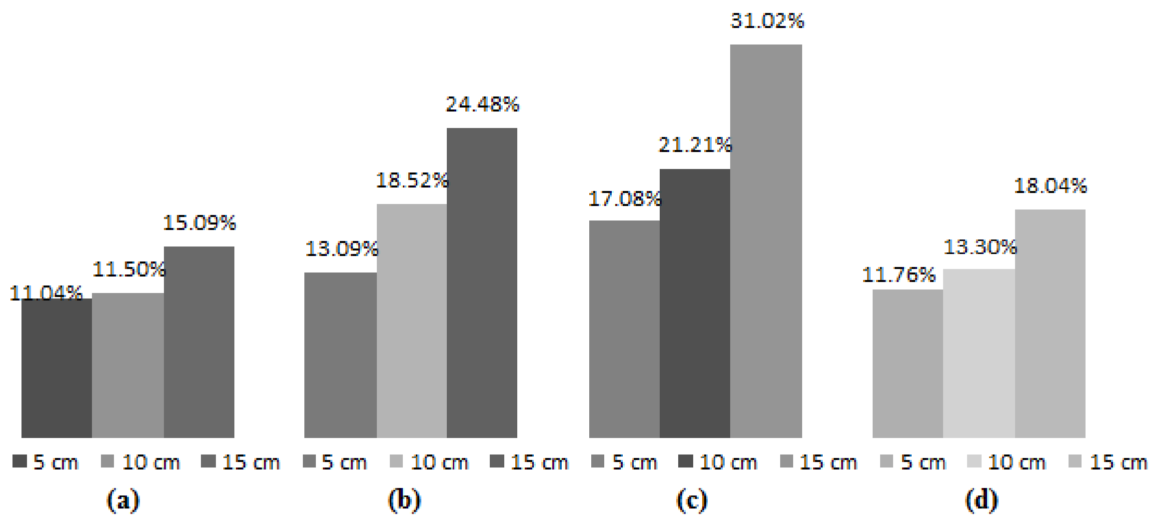

Figure 10: Experimentally determined burning efficiency (mass of oil after burnt/initial mass of oil) (a) oil/snow = 0.5:1 and snow packing density = 0.5 g/ml (b) oil/snow = 1:1 and snow packing density = 0.5 g/ml. (c) oil/snow = 1:1 and snow packing density = 0.7 g/ml. (d) oil/ snow = 0.5:1 and snow packing density = 0.7 g/ml.

The following observations can be made based on the results shown in Fig. 10:

1. Given a snow packing density and oil to snow ratio, the burning efficiency increases with an increase in diameter. This is due to an increase in the surface area for heat transfer from the

flame to the snow-oil surface. The increase is pronounced for the cases with higher oil to snow ratios (cases b and c), where around 87% and 81% increase in efficiency is observed when the diameter increases from 5 cm to 10 cm and further to 15 cm, respectively. For the lower snow to oil ratio (0.5:1) shown in cases a and d, it is observed that the increase in efficiency is smaller (47% increase in case a 53% increase in case d).

2. The maximum burning efficiency is obtained for case c with highly packed snow (0.7 g/ml), with higher oil to snow ratio (1:1). In this case, the oil does not penetrate towards the bottom of the container and therefore is able to burn steadily. However, the efficiency (~31 % for D = 15 cm) is significantly lower than that observed for a case with no snow where 100% efficiency was achieved. The reason is further explained in the next section where burning behavior is physically explained.
3. The lowest burning efficiencies are observed for the case a, where snow packing density is low (0.5 g/ml) and the oil to snow ratio is also low (0.5:1). In this situation, since the snow is highly porous, the oil tends to sink down to the bottom. Further since the oil to snow ratio is also low, very little oil remains at the surface, which is why overall efficiency is also reduced.
4. From a practical ISB perspective, highly packed snow and high oil to snow fraction is the preferred for imparting efficient clean up of the oil by burning. As discussed in the next section, the vessel rim seems to play a significant role in this case. It is likely that for situation in the field, such rim effects will not occur, as the spill on snow will be unconfined when ignited.

General evolution of the combustion

High packing density case

As discussed earlier with respect to Fig. 6(b) and 6(d) that the burning rate of high snow - packing density cases are higher, especially for oil-snow ratio of 1:1 [Fig. 6(b)]. The schematic of the evolution of burning process and the estimated physics in the case of the high snow packing density case, based on visual observation of the burning behavior, mass loss rate data and in depth temperature profiles, are shown in Fig. 11. The following phases are observed:

Phase 1: Oil dispersion prior to ignition

Initially, when oil is poured over the snow, it accumulates at the top surface as shown in Fig. 11a due to high packing density of snow. The concentration of oil in the snow is higher at the top surface, remains almost constant over its thickness (no mixing with snow) and further decreases along the depth as shown in Fig. 11a.

Phase 2: Ignition

On ignition of the oil surface using a butane torch at its center, a diffusion flame spreads across the entire diameter of the vessel, and is anchored around the circumference (Fig 11b). A photograph of the flame immediately after ignition is shown in Fig. 12. Two effects are observed: (1) as depicted by the thermocouple readings shown in Figure 7(B), the temperature of the region close to TC 1 increases rapidly close to the boiling point of the liquid in around 160 s. Secondly, the snow melts and water formed starts accumulating below the oil layer at the surface. Since the snow is densely packed, the water does not flow down to the bottom of the surface immediately. In addition, the flame begins to heat the rim of the vessel. As shown in Fig. 7(B), the temperature of TC's 5 and 6 before ignition are well below the melting point of snow (~ -10ºC). However, after ignition the temperature rises above 0^{o}C in a duration of around 50 s. TC 5 and TC 6 indicates that their temperatures increase to around 15^{o}C, as the surface of the oil reaches close to its boiling point around 160 s. This facilitates the melting of snow attached to the rim and a circumferential cavity is subsequently formed as shown in Fig. 12.

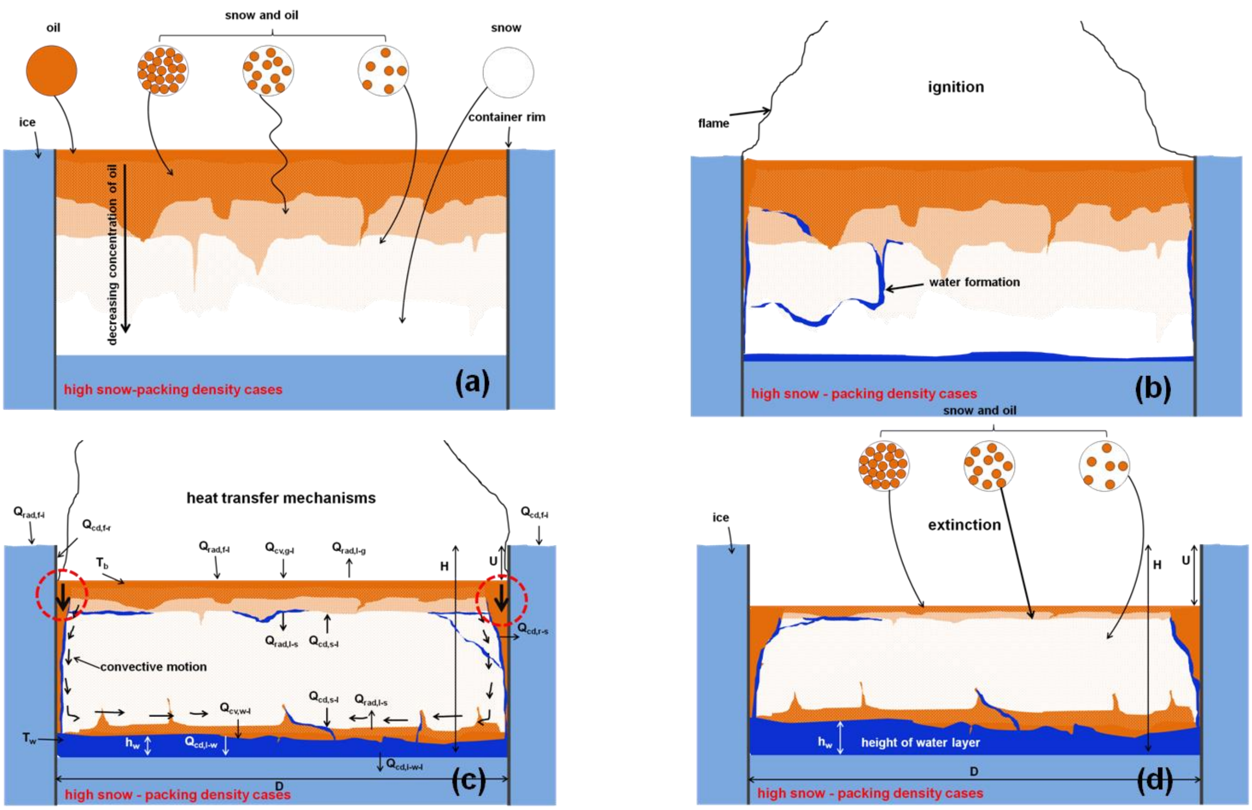

Figure 11: Evolution of combustion for high snow packing density

Phase 3: Steady burning

After ignition, the oil-snow mixture steadily burns for some time as shown in the photograph in Fig. 12. For the high snow-packing density, oil at the top of the snow remains quite homogeneous and the oil layer burns steadily at the surface of the snow without penetrating much into it. As shown in Fig. 11c several heat transfer mechanisms come into play at this stage. The most dominant one in the condensed phase is, however, caused because of the heating up of the vessel rim predominantly by conduction heat transfer from the flame.

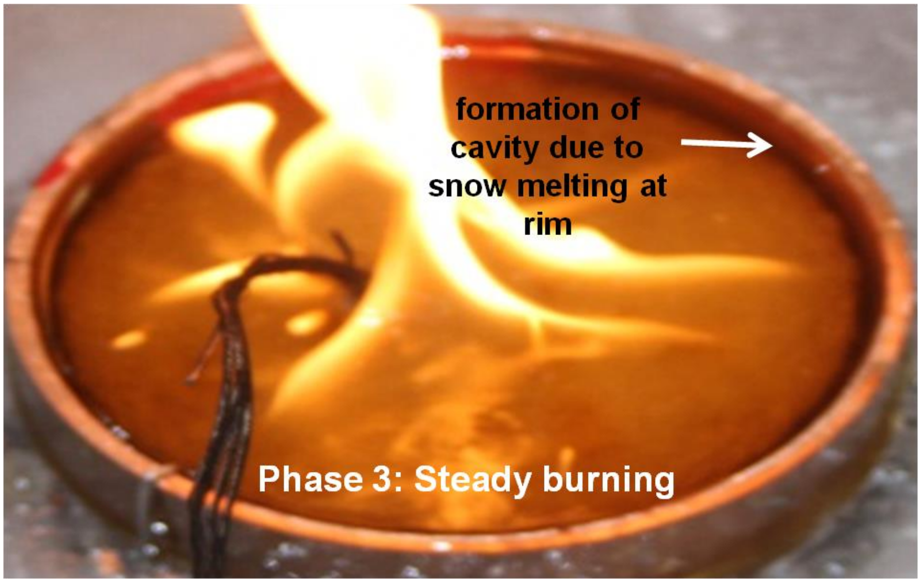

Figure 122: Burning of the snow-oil mixture for the high snow- packing density case

The vessel rim gets heated up quickly after ignition due to conductive heat flux from the flame, which anchors around the rim. The hot rim causes the snow in contact with it to heat up and melt. Further, since the inner container is made of copper, a good conductor of heat, the flame heat flux is effectively transferred throughout the vessel rim thickness, which is the direction of least resistance to heat transfer. This causes formation of a cavity close the wall of the vessel, due to melting of snow and the transport of water beneath the snow layer, as shown in Figs. 11(c) and 12. The oil layer at the surface is able to run down along with the water through the side cavity, thereby causing a decrease in the oil thickness at the surface. This movement of oil shown schematically in Fig. 11c by the red-dashed circle, is one of the main reasons for the reduction in burning efficiency. The movement of the oil sideways is supported by gravity and to some extent by Marangoni convection effects, which is caused due to significant temperature gradient on the oil surface. The temperature data shown in Fig. 7B clearly shows the increase in the wall temperatures (TC 5 and TC 6). Further, TC 4 located at the bottom is consistently higher than TC 3, which is located above TC 4 after about 100 s. This shows that a warmer liquid oil-water accumulates at the bottom. Since the snow – packing density is high, the movement of the hot oil is most likely only through the sides, as explained earlier. The oil layer thickness reduces because of the combined effects of burning and the flow of oil downwards along the wall. After a critical reduction in the layer thickness, extinction occurs.

Phase 4: Extinction

Figure 11d shows a schematic of the change in oil-snow mixture concentration at extinction. As discussed earlier, a significant quantity of oil accumulates at the bottom of the due to cavity formation at the sides of the vessel. At extinction, the concentration of the oil is more at the bottom than at the top. Since the snow packing density is high and the temperature at the bottom is not high enough, the oil accumulated at the bottom is unable to diffuse upwards at fast enough rates to sustain combustion.

It should be noted that in spite of the deleterious effect of oil transport towards the bottom, the burning rate of the high packing density case is much higher than the low packing density cases.

Low packing density case

The initial oil to snow ratio is a significant parameter in the burning dynamics for the low packing density cases. When the packing density of the snow is low, or in other words the snow is highly porous, the oil seeps down to the bottom of the container. Therefore, as mentioned earlier, the concentration of the oil is higher at the bottom and lower at the surface, especially for low oil to snow ratio case. However, if the oil to snow ratio is 1:1, the oil concentration becomes homogenous throughout the snow and the snow behaves as a porous wick. The description of the burning dynamics for the two cases is discussed in this section.

Low oil-snow ratio

Based on visual observation of the burning behavior, mass loss rate data and in depth temperature profiles, an illustrative sketch of the evolution of the combustion process in the case of low snow-packing density (0.5 g/ml) and low oil to snow ratio (0.5:1) is shown in Fig. 13. The following phases are observed:

Phase 1: Oil movement prior to ignition

Initially, when oil is poured over the snow, it sinks down through the pores due to the action of gravity, as shown in Fig. 13(a). The concentration of oil within the snow is thus low at its top and increases along the depth, and be the highest at the bottom. Because of this behavior there is a practical difficulty in the onset of the ignition and sustaining of the burning.

Phase 2: Ignition

The oil is ignited using a butane torch at the center of the top surface. The flame does not spread across the entire diameter of the vessel, as in the high packing density case. Instead, a small, localized pool flame is sustained around the centre, as shown in Fig. 13(b). A photograph of the flame at 50 s after ignition is shown in Fig. 14. It is clear that the burning rate is very low. The transport of the oil from bottom to top is by capillary action as depicted in Fig. 13(b). Predominantly through the centralized flame and partially during ignition by propane torch, the snow at the top surface has melted. Liquid oil gets heated up by the flame over it and further melts the snow. The water being denser seeps down to the bottom displacing more oil to come to the surface. This causes increase in the burning rate [Fig. 6(c)]. Transport of oil and water are more by convective transport as the snow is loosely packed. Since the flame does not propagate to the entire vessel, heating of rim is not observed.

Phase 3: Steady burning

After ignition, the oil-snow mixture burns essentially by increasing the melt area formed during ignition as shown in Figs. 13(b) and 13(c). The melt area grows because of the flame heat flux and facilitates consequent release of oil trapped in the pores. As the size of the flame increases, the rate of melting increases which correspondingly results in more oil reaching the surface and burn. As a result, the mass burning rate is enhanced as observed in Fig. 6(c). The flame moves down as the surface recedes and a very short steady burning regime is observed. The increasing rate of burning rate and its decreasing rate after reaching a maximum, are rapid for low packing density cases. Rim heating is almost absent, as indicates by TC 5 and TC 6 in Figs. 7(a), 8(a) and 9(a).

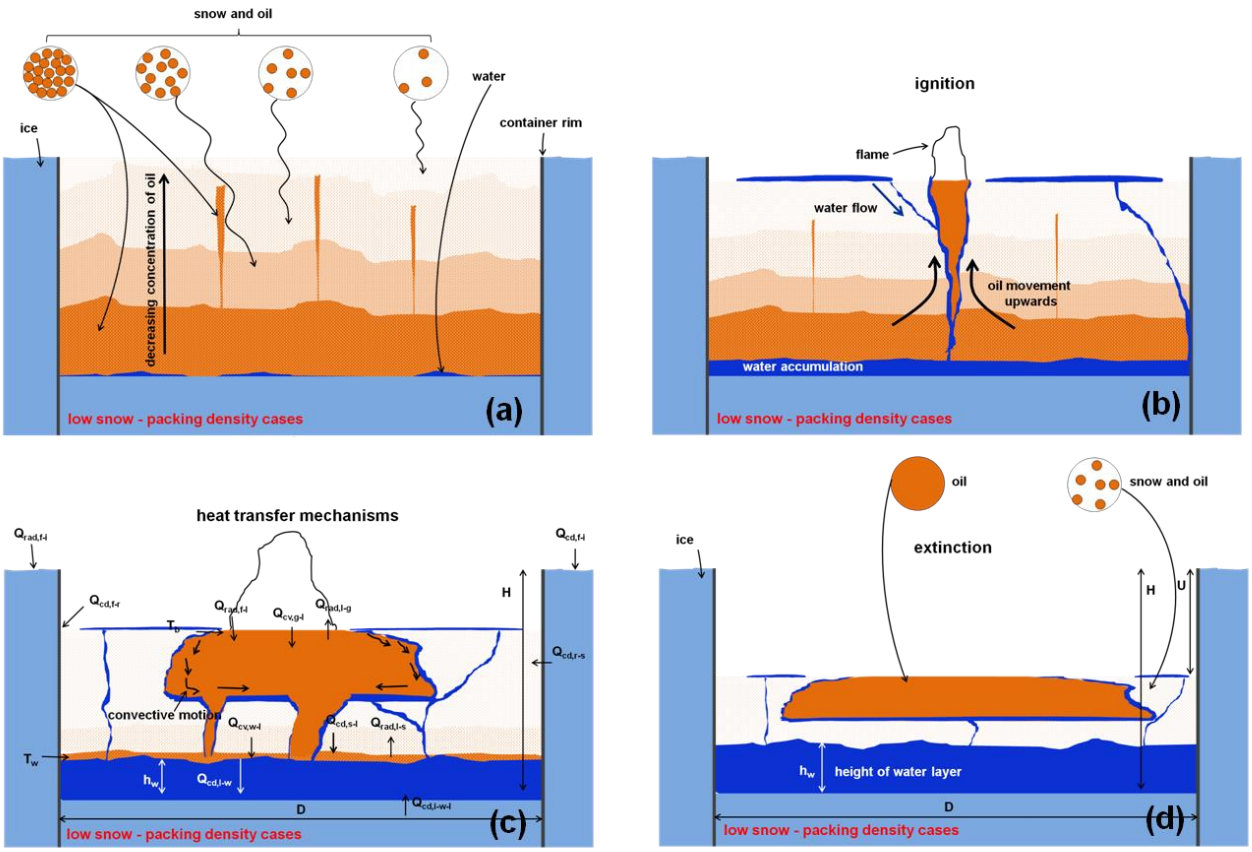

Figure 133: Evolution of combustion for low snow packing density

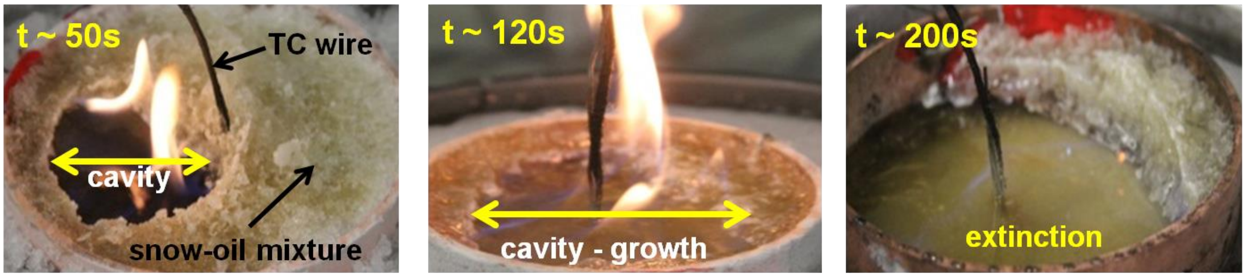

Figure 144: Photographs of burning observed in for a low-packing density (0.5 g/ml) and low oil/snow (0.5:1) case.

Phase 4: Extinction

Figure 13(d) shows a schematic of the stature of oil-snow mixture concentration at extinction. As the burning progresses, the surface area of the melt increases and water thus formed seeps towards the bottom. Since for this case, the oil content is less, snow-water mixture surrounds the flame. The little quantity of oil left over is also cooled significantly by surrounding snow/water mixture both from sides as well as from bottom, and as a result, vaporization is curtailed and the flame gets quenched due to thermal extinction.

High oil/snow ratio

Based on visual observation of the burning behavior, mass loss rate data and in depth temperature profiles, an illustrative sketch of the evolution of the combustion for the low snow-packing density case containing high oil/snow ratio (i.e., 0.5 g/mL and 1:1 oil/snow ratio) is shown in Fig. 15. The following phases are observed:

Phase 1: Oil movement prior to ignition

Initially, when the oil is poured over the snow, it sinks down as shown in Fig. 15(a). The concentration of oil in the snow is equally distributed from top of the snow layer to its bottom due to the high volume of oil and low snow packing density. Further, there is a very thin layer of oil alone at the top having a thickness of around 3 mm to 5 mm, as shown in Fig. 15(a).

Phase 2: Ignition

Once the oil is been ignited, the flame spread across the entire diameter of the vessel, as in the cases of high snow density, due the presence of the thin oil layer. This is shown in Fig. 15(b). A photograph of the flame at 50 s after ignition is shown in Fig. 16. It is clear that the burning rate will be higher than the previous case, as a result of the burning of increased oil surface, compared to the low oil-snow ratio case. Since the snow is loosely packed, the transport of water and oil is fairly rapid. As the oil evaporates, the molten snow seeps to the bottom of the oil bound snow layer, as shown in Fig. 15(b). No heating of the vessel rim, nor the formation of cavity as in the high packing density case, is observed, as the flame does not extend towards the rim and anchors on the oil surface itself. This is also due to the transport of water through the pores itself, which always leave a pure layer of oil available on the top.

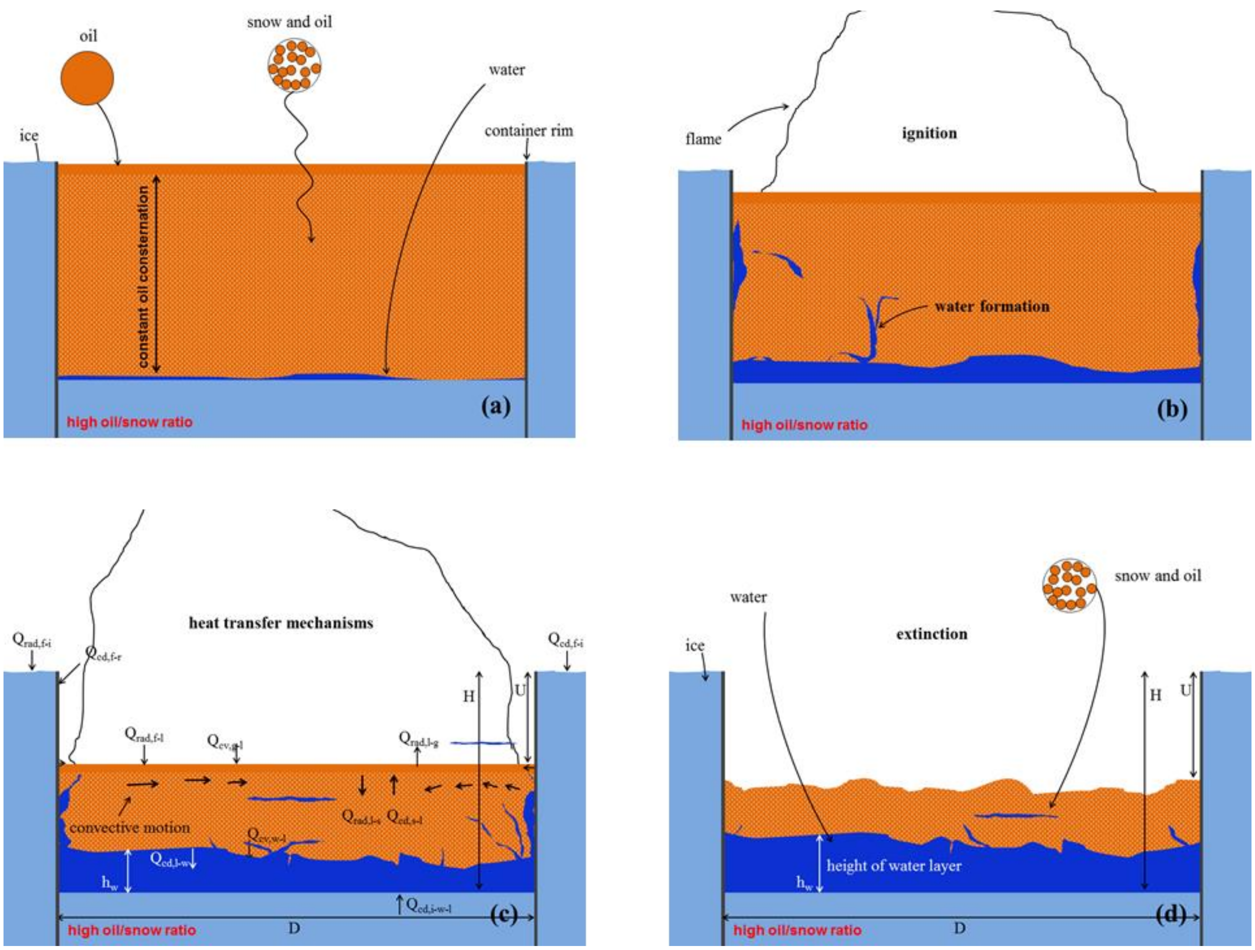

Figure 155: Evolution of combustion for high oil/snow ratio

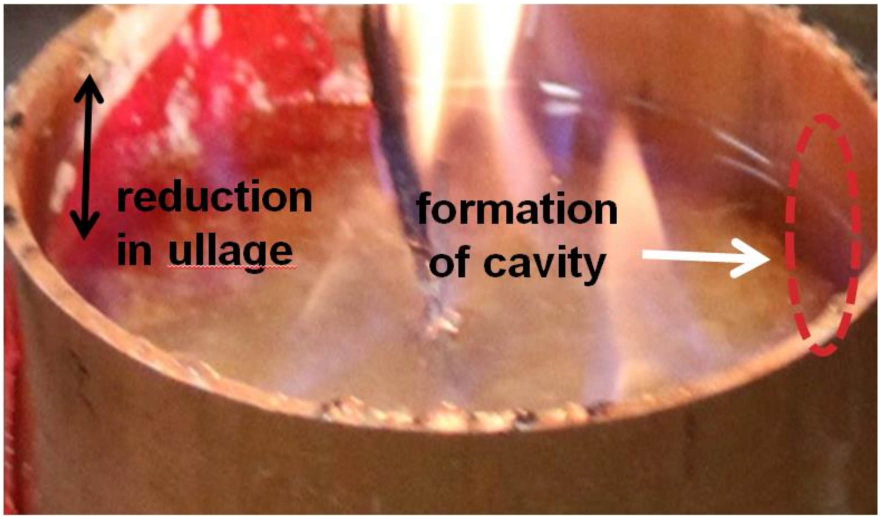

Figure 166: Burning of the snow-oil mixture for the high oil/snow ratio case

Phase 3: Steady burning

After ignition, the oil-snow mixture steadily burns for quite some time as shown in the photograph in Fig. 16. Due to increased availability of oil in this case, and the continuous formation of oil layer at the top, the steady burning regime is longer as compared to the case with oil-snow ratio of 0.5:1. As shown in Fig. 15(c) several heat transfer mechanisms come into play at this stage. Some of the oil in the oil layer at the surface is able to run down along with the water through the pores in the layer thereby causing an additional decrease in its thickness at the surface, apart from being consumed by the burning process. This convective movement of oil is shown schematically in Fig. 15(c).

Phase 4: Extinction

Figure 15(d) shows a schematic of the change in oil-snow mixture distribution at extinction. The oil layer thickness decreases beyond a critical value and is further cooled by the cold wall as well as by the cold water at the bottom. This suppresses the vaporization rate and thus, the transport of fuel vapors to the flame. The flame gets extinguished subsequently.

Chapter 4 Conclusions and Future Work

Since 1973 and the United States has suffered from oil spilling during the oil exploration process, which is still ongoing. Many other countries have signed with multiple companies to explore oil especially in the Arctic region. This region is very difficult to arrive to and deliver the equipment required in case of the spilled oil clean up. ISB is the most optimum solution as it produces more than 90% burning efficiency.

Oil spill can occur over land (i.e. sand, ice, or snow) or over water. The focus of this project has been to understand the oil burning behavior over snow. There are a few research studies related to this topic; however, no detailed studies have been traced to reveal the influence of snow packing density on oil burning behavior. To understand this influence, three parameters have been chosen; the oil/snow ratio, pool diameter, and snow packing density. Each parameter have been varied in different range of values and tested for three times to end up with 12 sets and 36 experiments.

Experimental data in the form of mass loss rate, in-depth temperature profiles, and flame photographs were used to further explain the burning dynamics. The mass loss rate data have shown that when the snow was highly packed, the mass loss rate started off with a high value and increasing which was due the presence of oil layer on the top surface. However, if the snow has a low packing density, the mass loss rate started off with a low mass loss rate value and this was due to the penetration of oil into the snow which blocked the oil from burning. The mass loss rate then increased very dramatically due to the snow cavity diameter was increasing. However, the mass loss rate peak was yet still almost as half of the mass loss rate peak when the snow was highly packed especially for larger pool diameter.

In depth temperature profile have shown that the top surface thermocouple has the highest temperature followed by the second thermocouple, however, the bottom thermocouple have shown to have greater temperature than the one above which was due to the penetration of oil through vessel edges and heating up the bottom thermocouple. This analysis was not observed for the small oil volume with the same snow packing density. The bottom thermocouple has less temperature than the one above it due to low volume of oil which could not reach the bottom thermocouple through the edges.

The burning efficiency has shown that the highest burning efficiency was observed when the snow packing density was high as well as the oil volume. This was due the top oil layer was taken enough time to burn rather than able to penetrate into the snow which would made the efficiency lower as was observed in low snow packing density case.

Even though the highest burning efficiency was observed when the snow packing density was high as well as the oil volume, however, there are still more burning efficiency can be observed if the vessel rim was not present. The rim was heating the nearby snow, which resulted in melting it and allowing the oil to penetrate through it to the bottom ice block and arriving the extinction sage earlier than it should be.

Future work is recommended to observe the oil burning behavior over snow in an open area where there is no rim can assist the oil to penetrate into the snow. This can be done as mention in an open area or in a larger vessel diameter where the pool fire diameter is no more than half of the vessel diameter.

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Appendix A

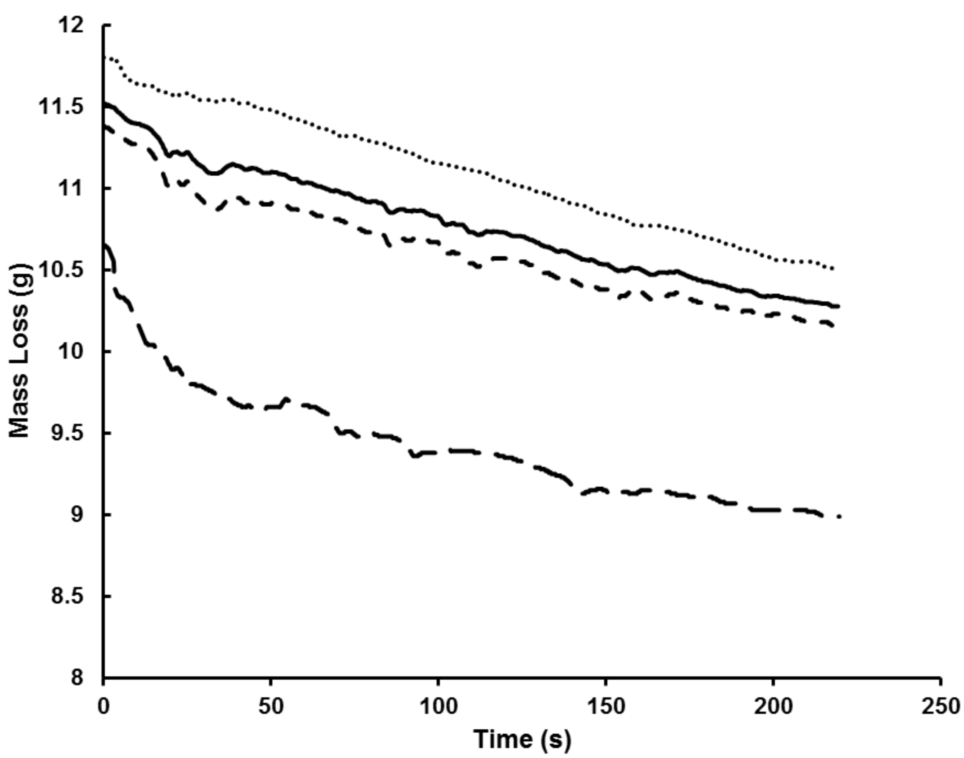
Experiment Description:

Weight ratio of oil to snow =0.5:1
Snow packing density =0.5 g/mL

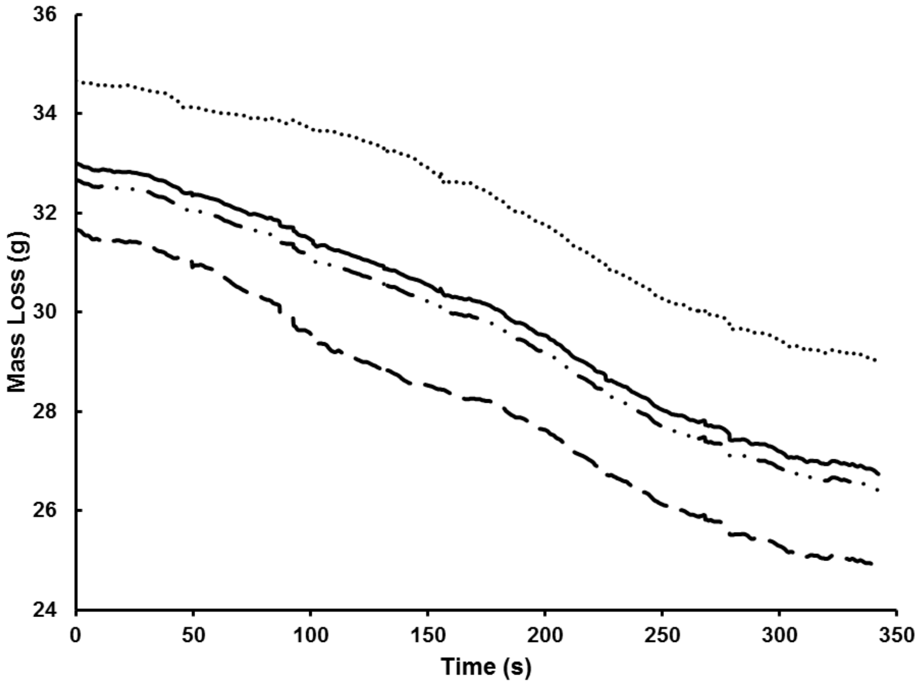
Mass Loss Vs. Time

Average
1st Trial
2nd Trail
3rd Trail

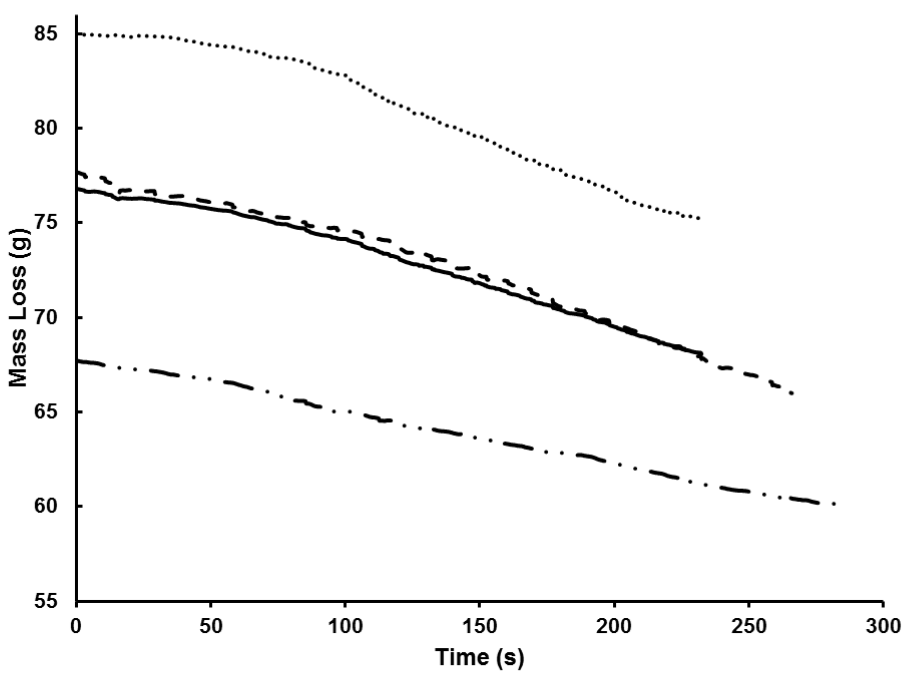
5 cm Container



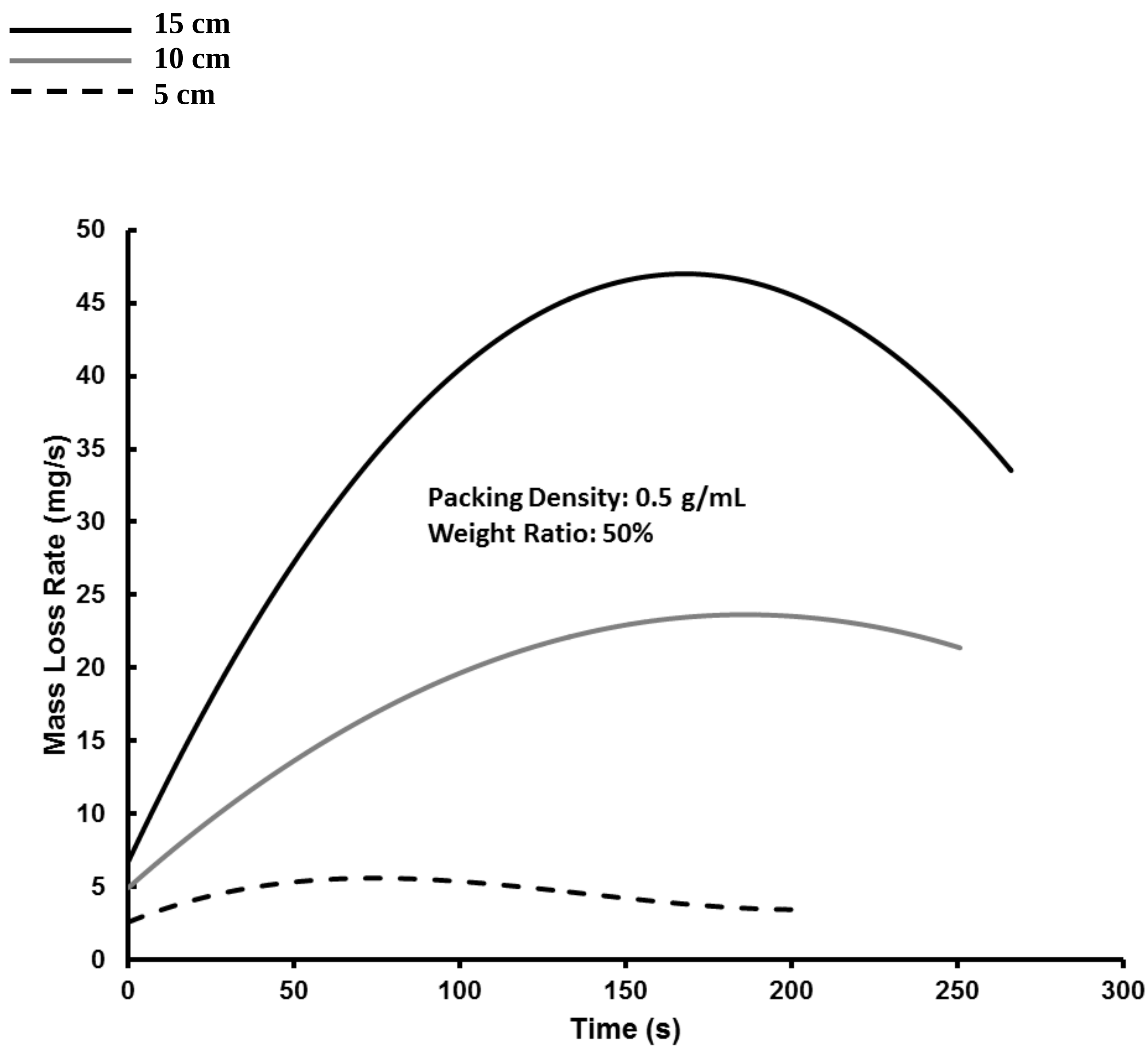
10 cm Container



15 cm Container

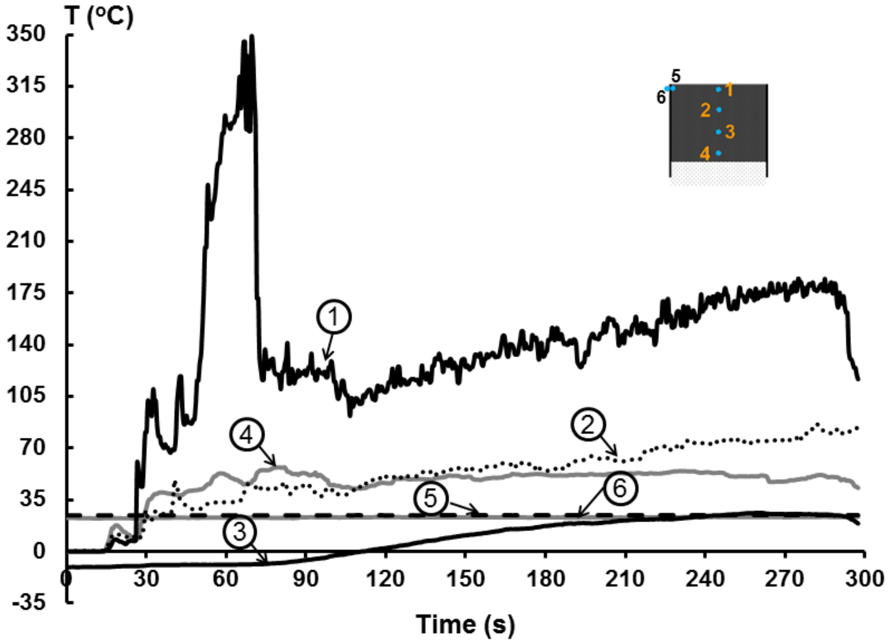


Mass Loss rate Vs. Time

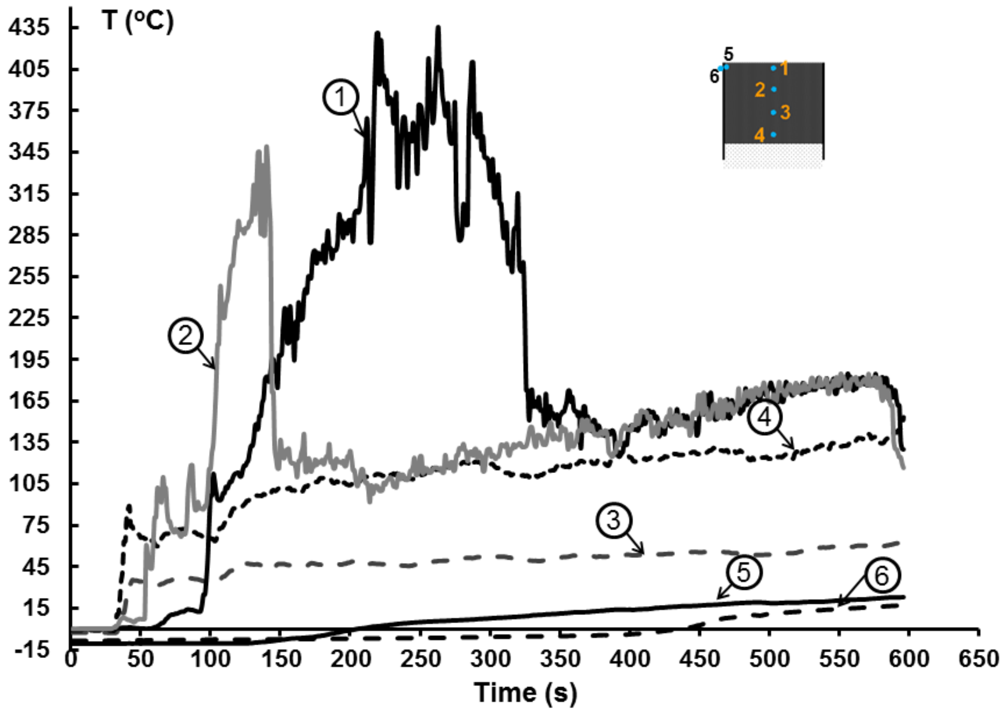


Temperature Vs. Time

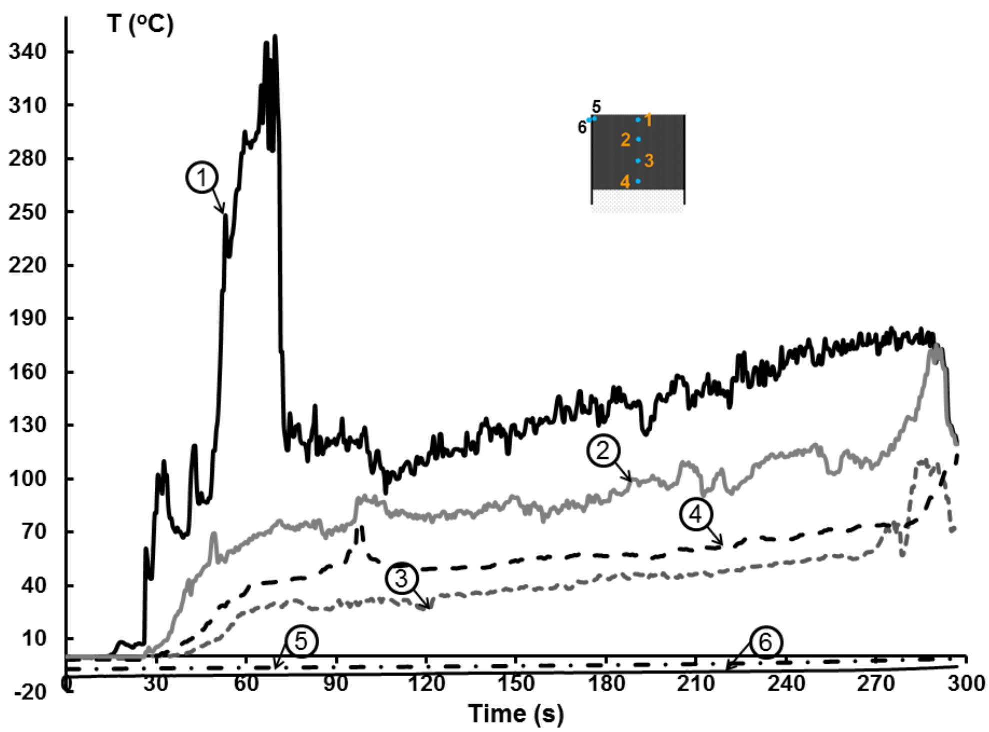
5 cm Container



10 cm Container

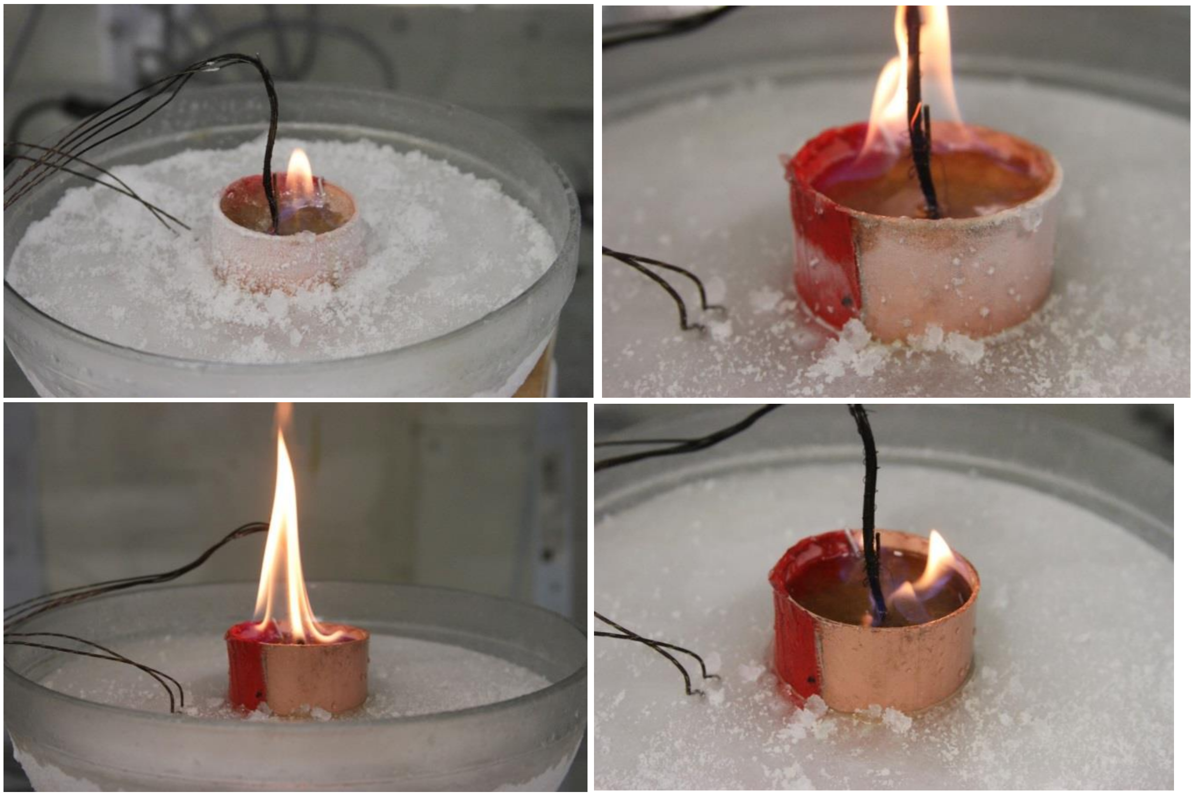


15 cm Container



Experiment Pictures

5 cm Container



10 cm Container

15 cm Container

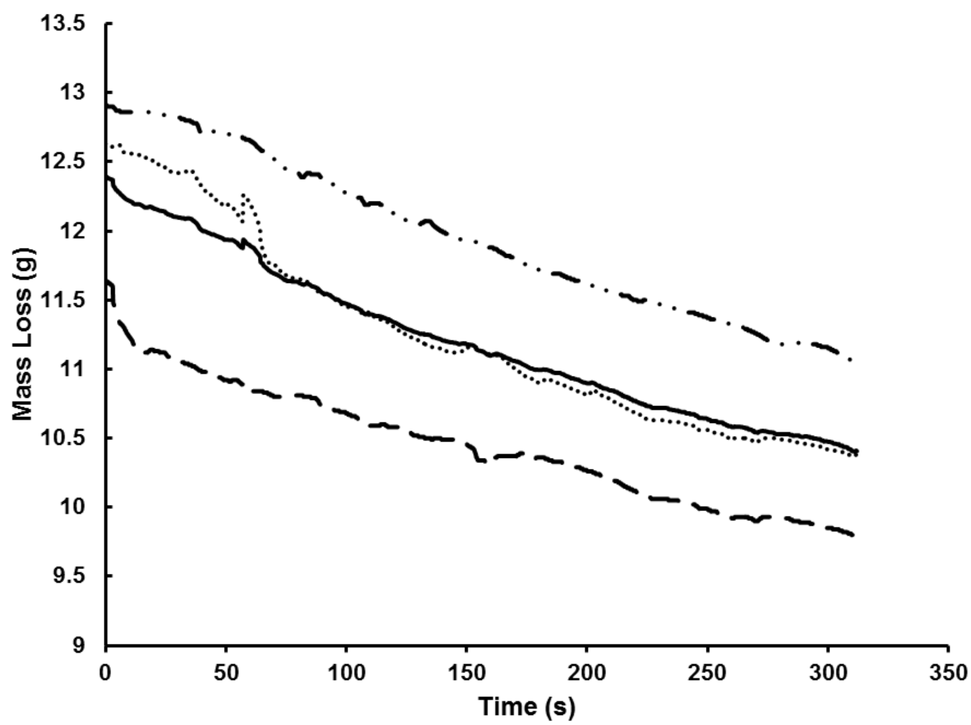
Experiment Description

Weight ratio of oil to snow= 0.5:1
Snow packing density= 0.7 g/mL

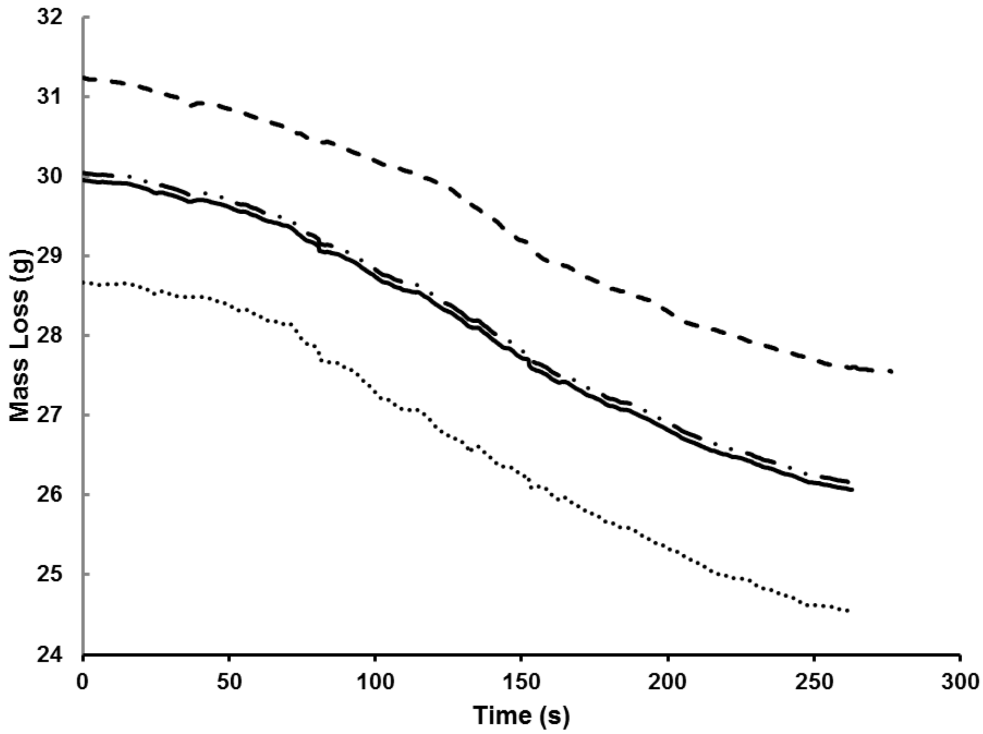
Mass Loss Vs. Time

Average
1st Trial
2nd Trail
3rd Trail

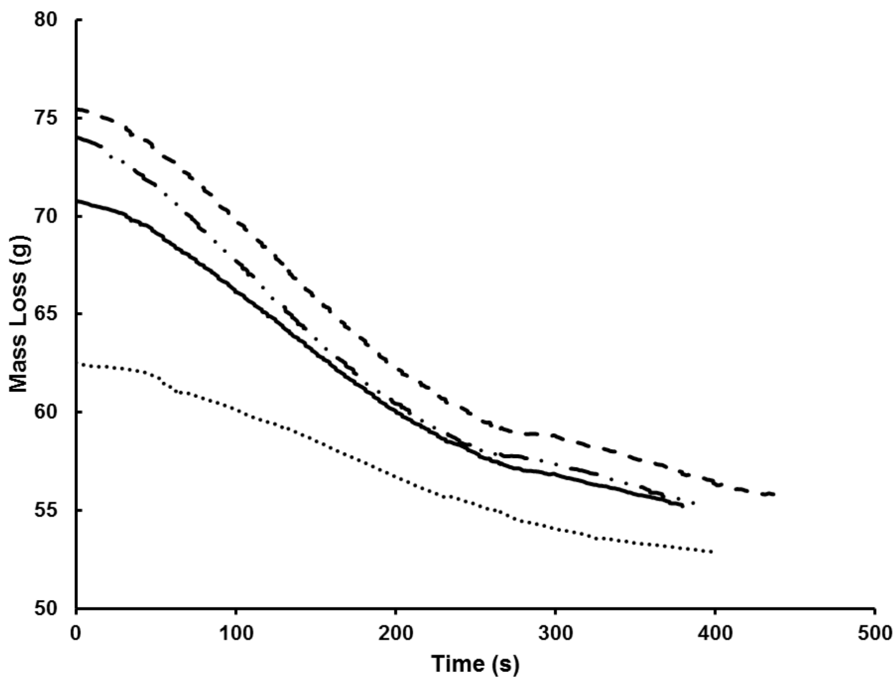
5 cm Container



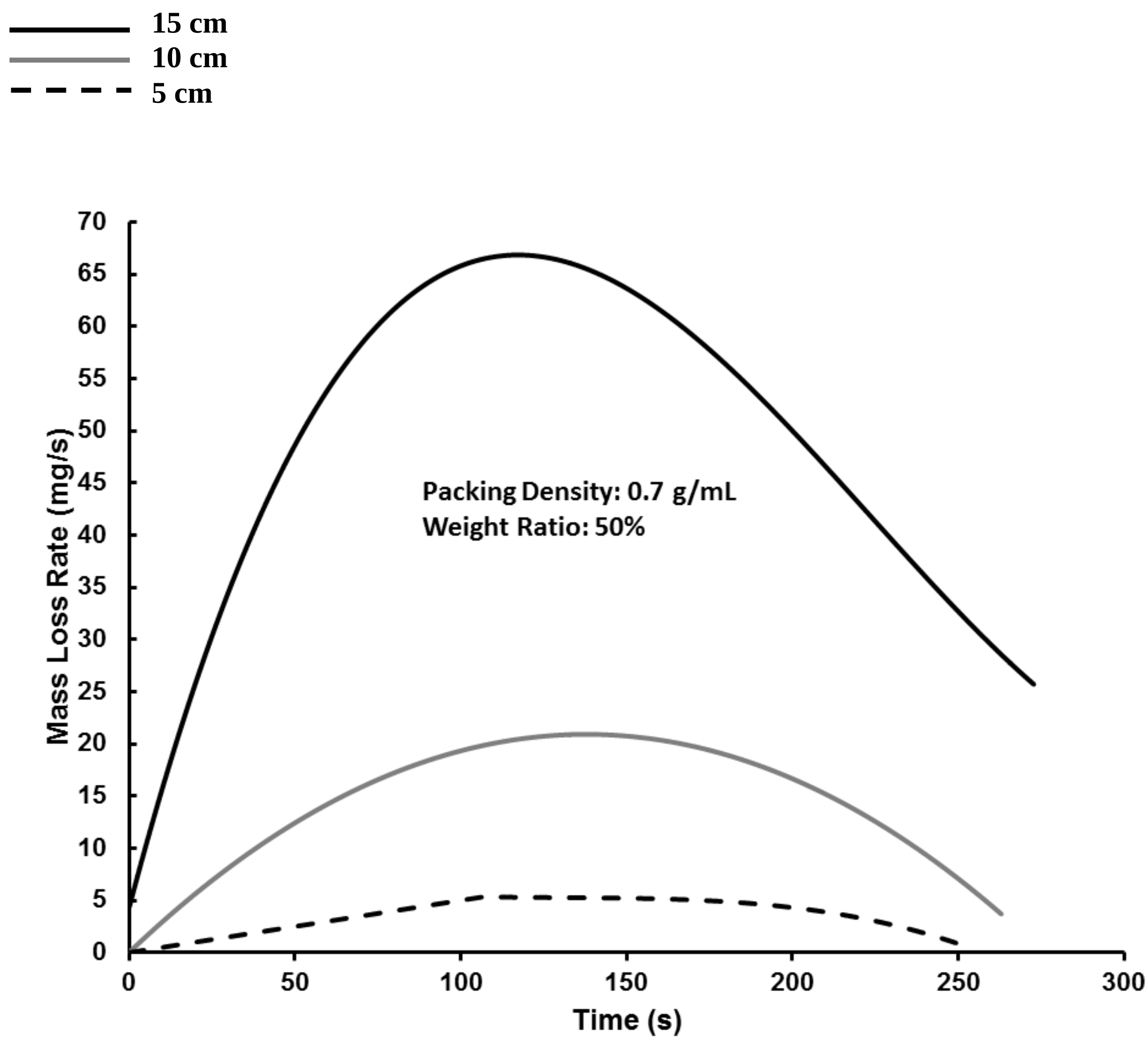
10 cm Container



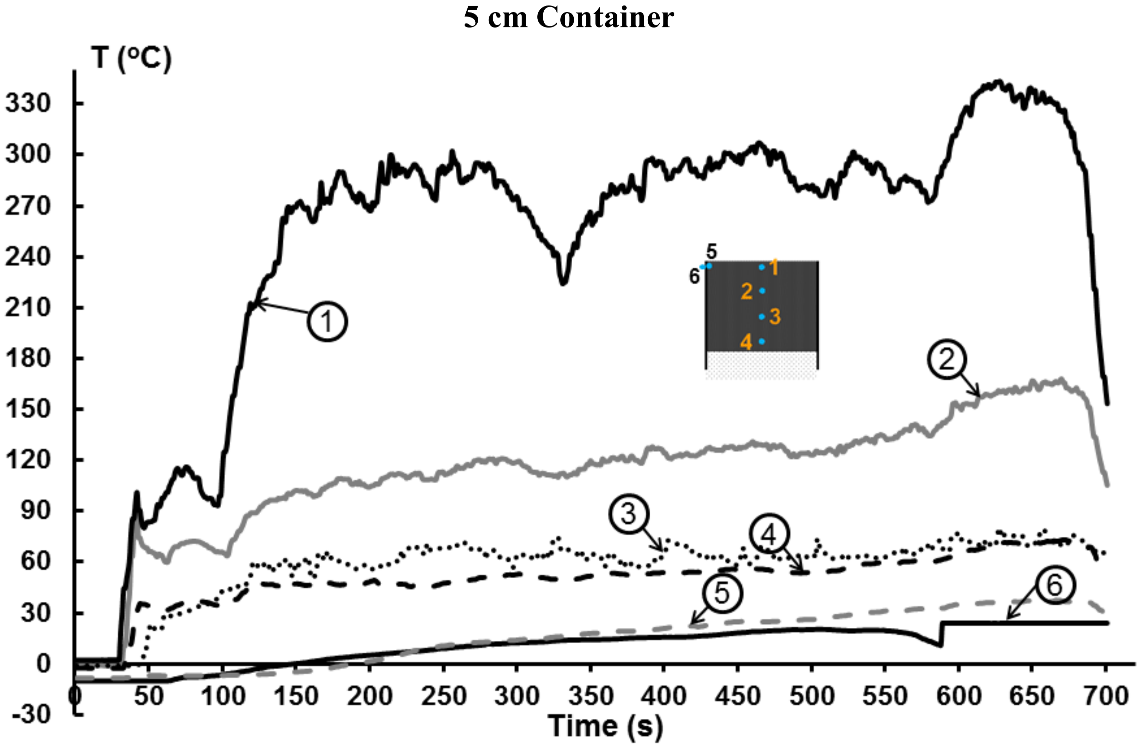
15 cm Container

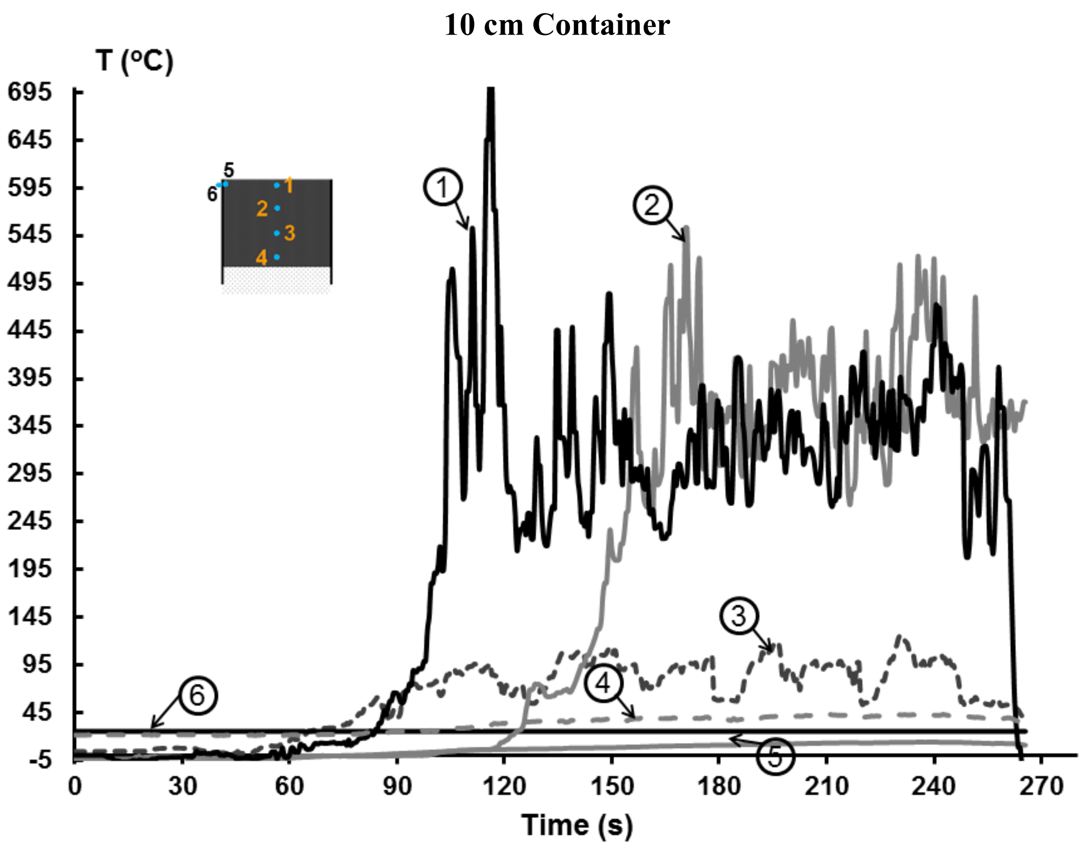


Mass Loss rate Vs. Time

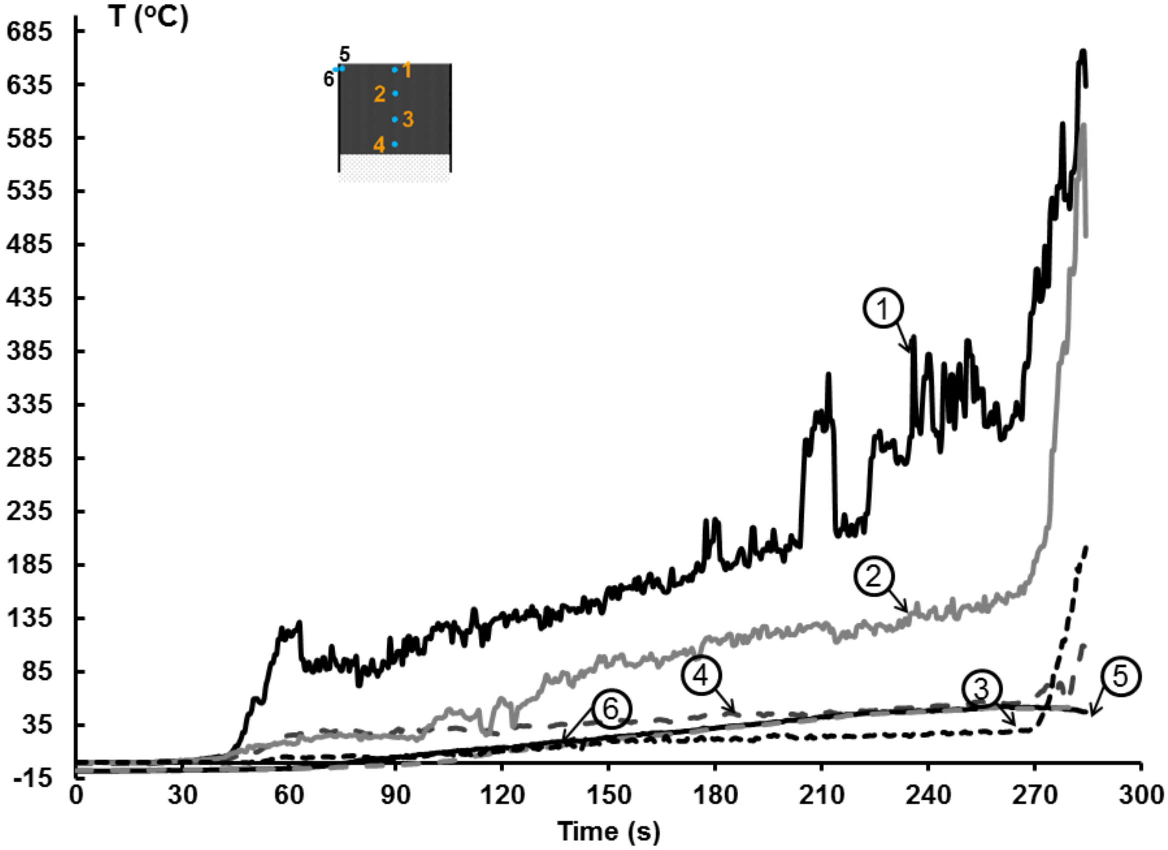


Temperature Vs. Time



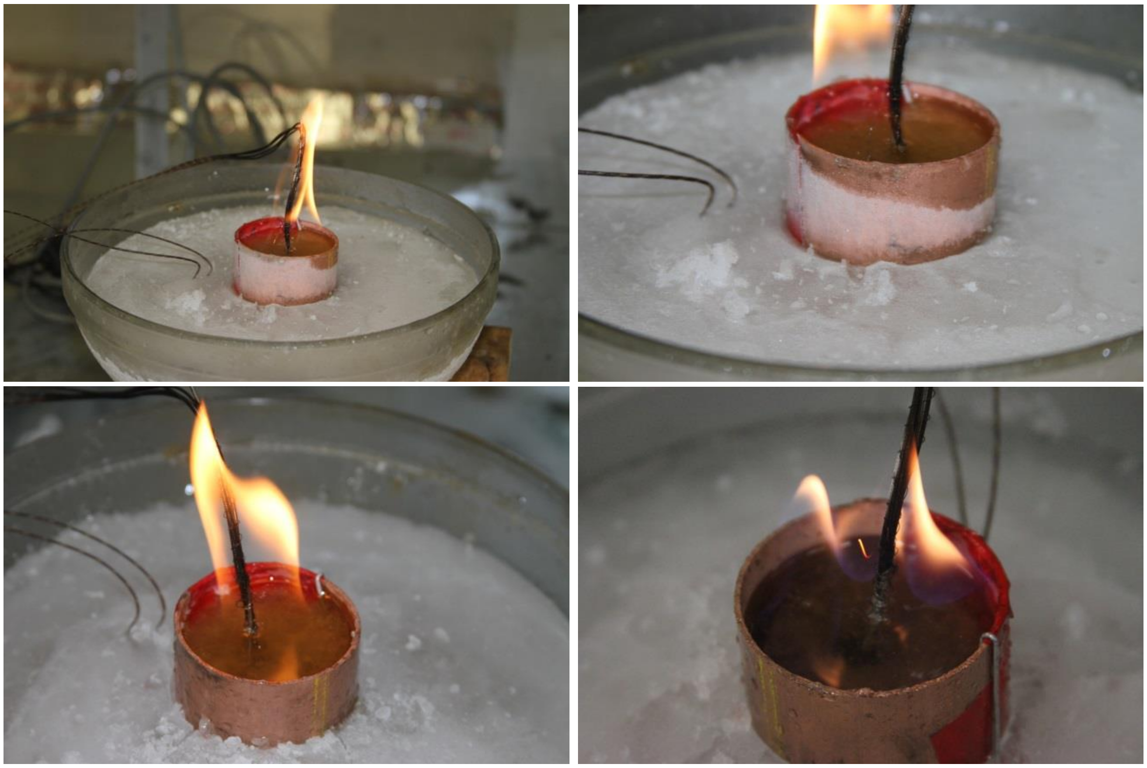


15 cm Container



Experiment Pictures

5 cm Container



10 cm Container

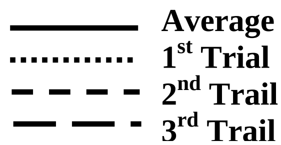
15 cm Container

Experiment Description:

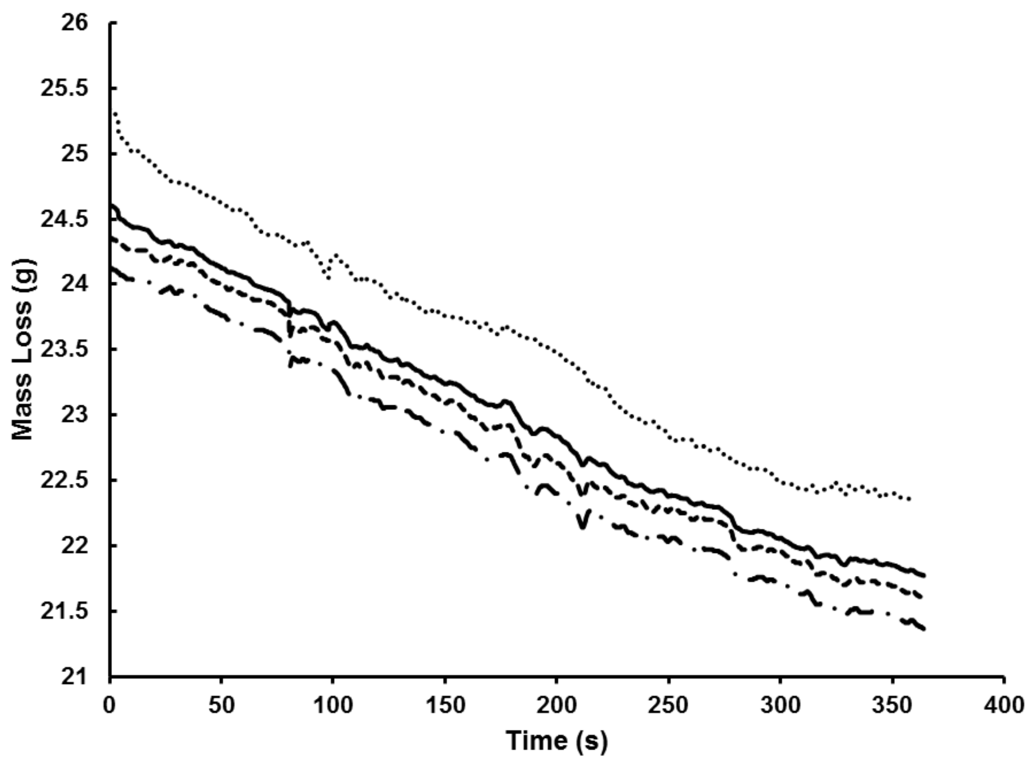
Weight ratio of oil to snow= 1:1

Snow packing density= 0.5 g/mL

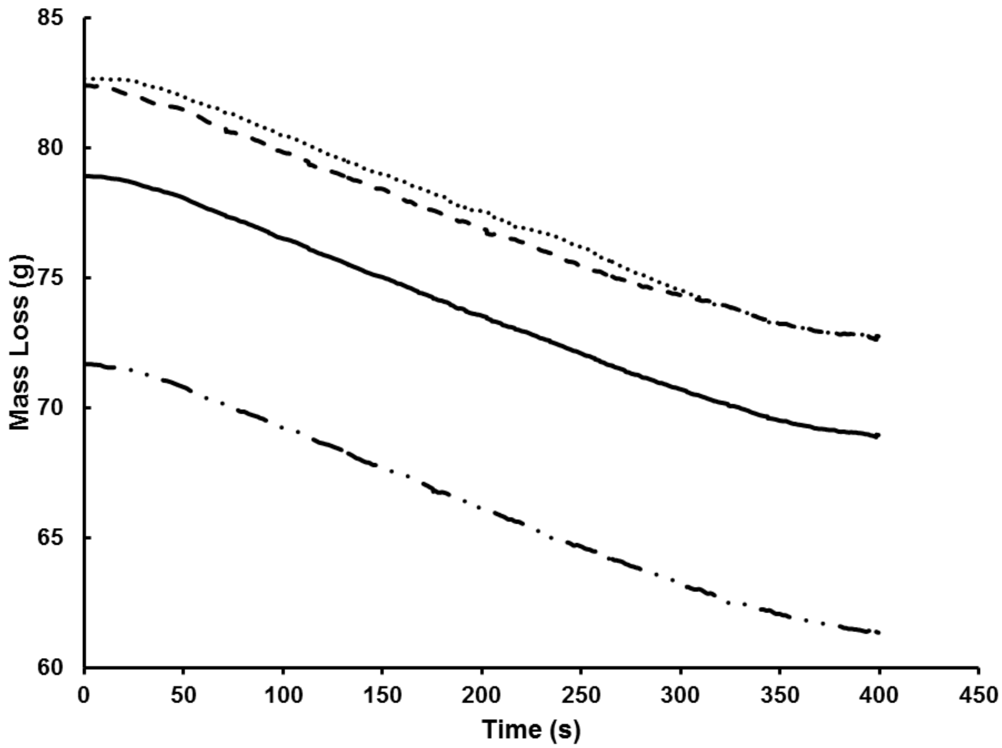
Mass Loss Vs. Time



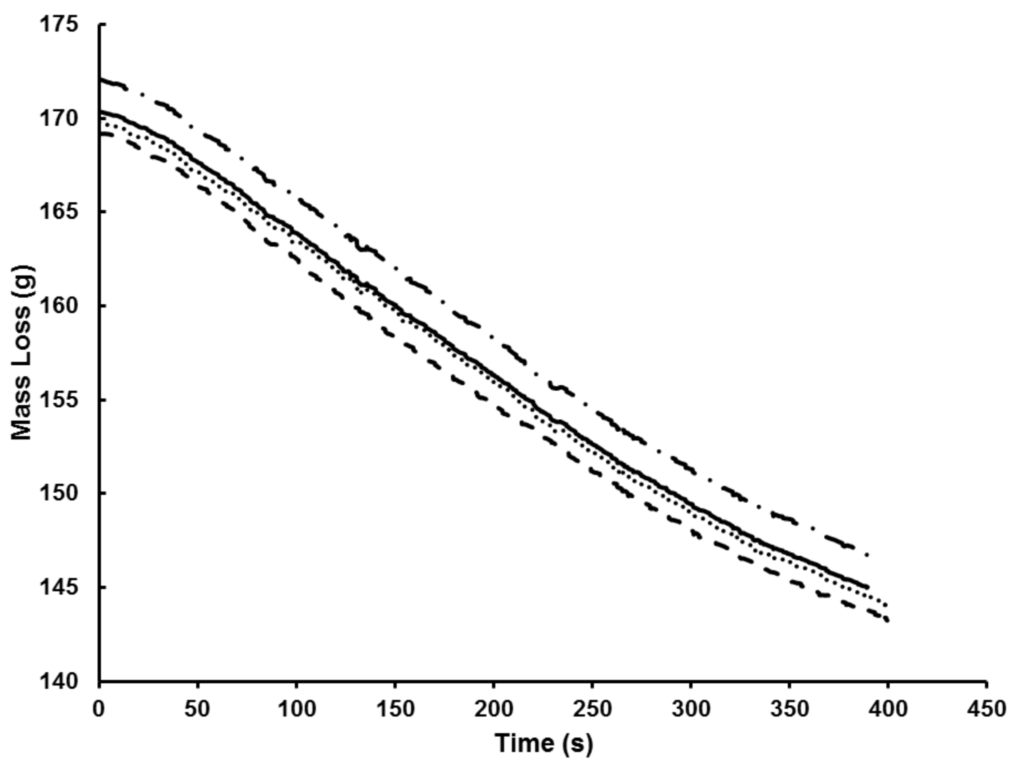
5 cm Container



10 cm Container

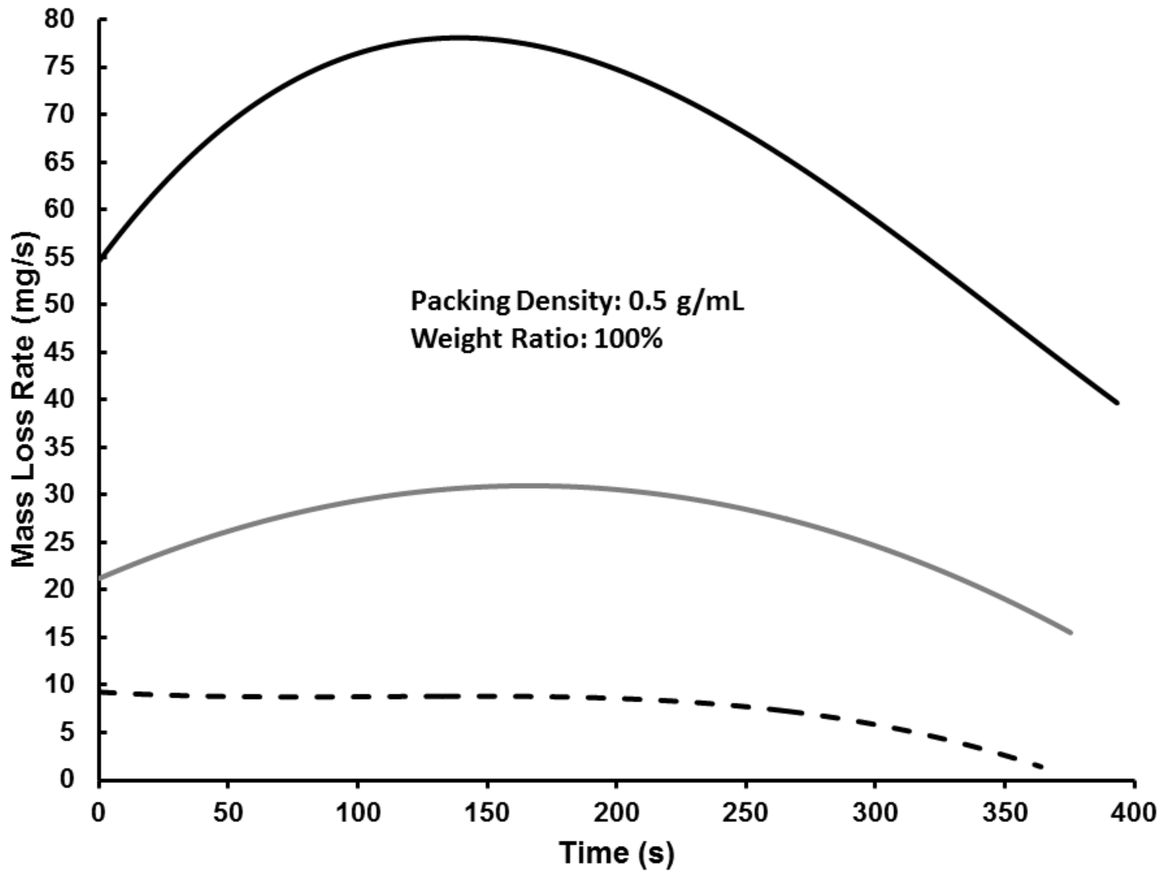


15 cm Container

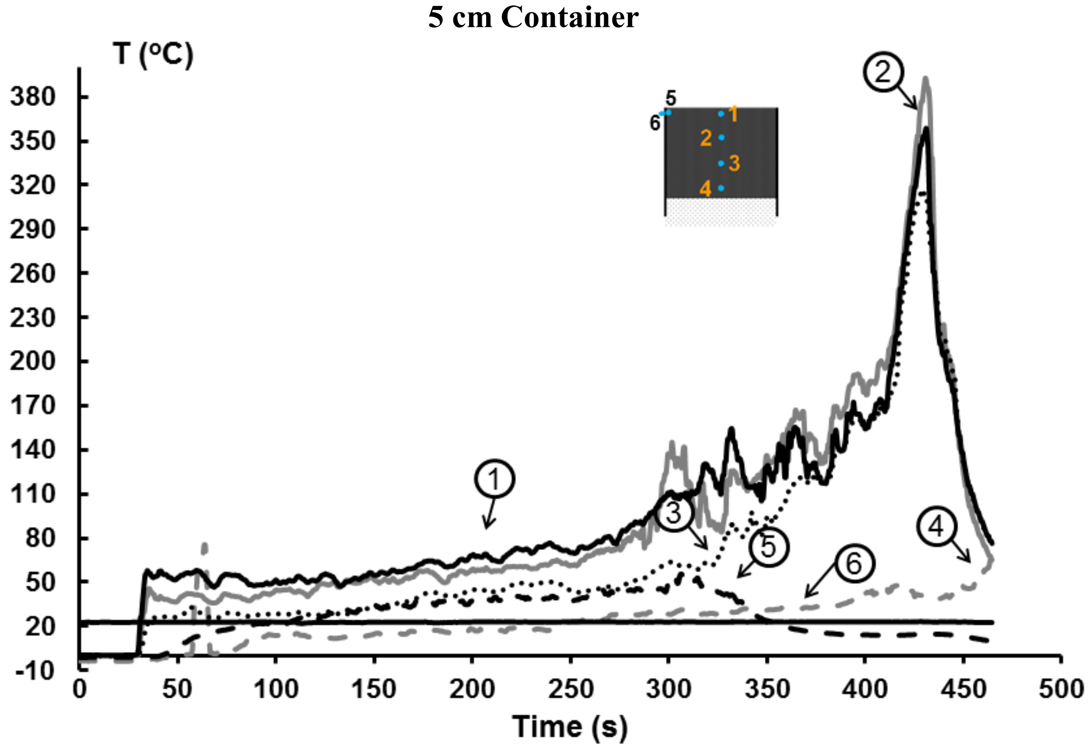


Mass Loss rate Vs. Time

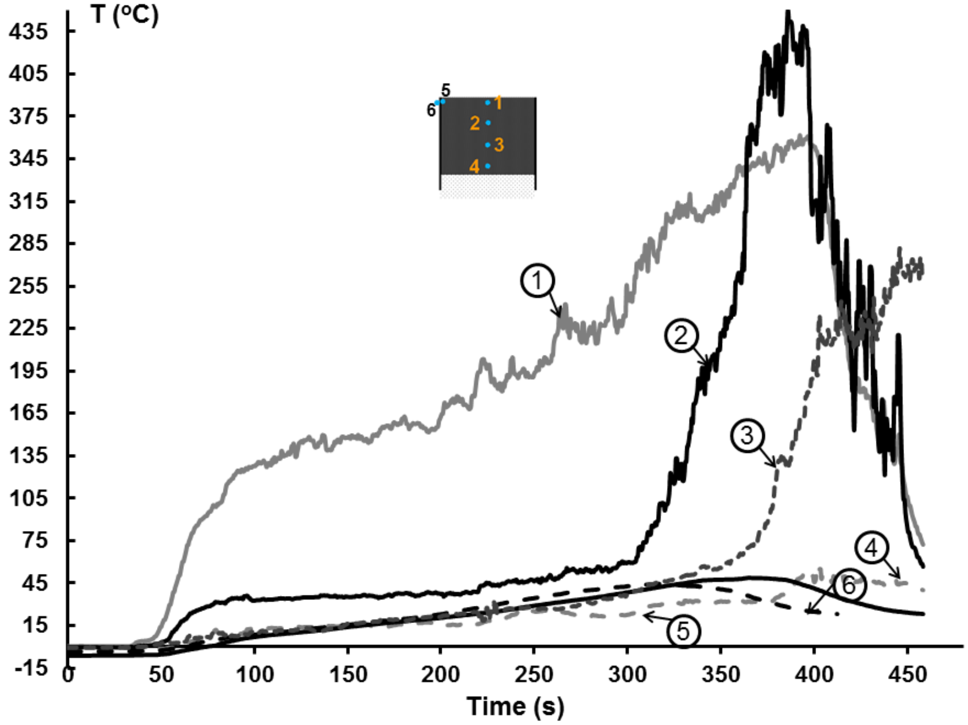
15 cm
10 cm
5 cm



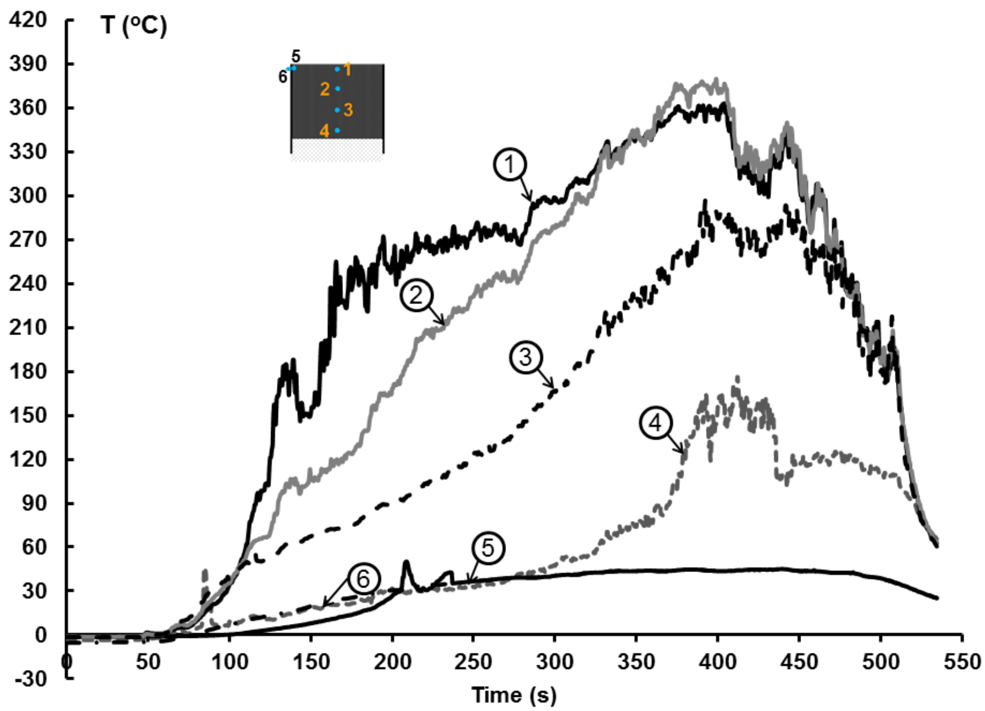
Temperature Vs. Time



10 cm Container

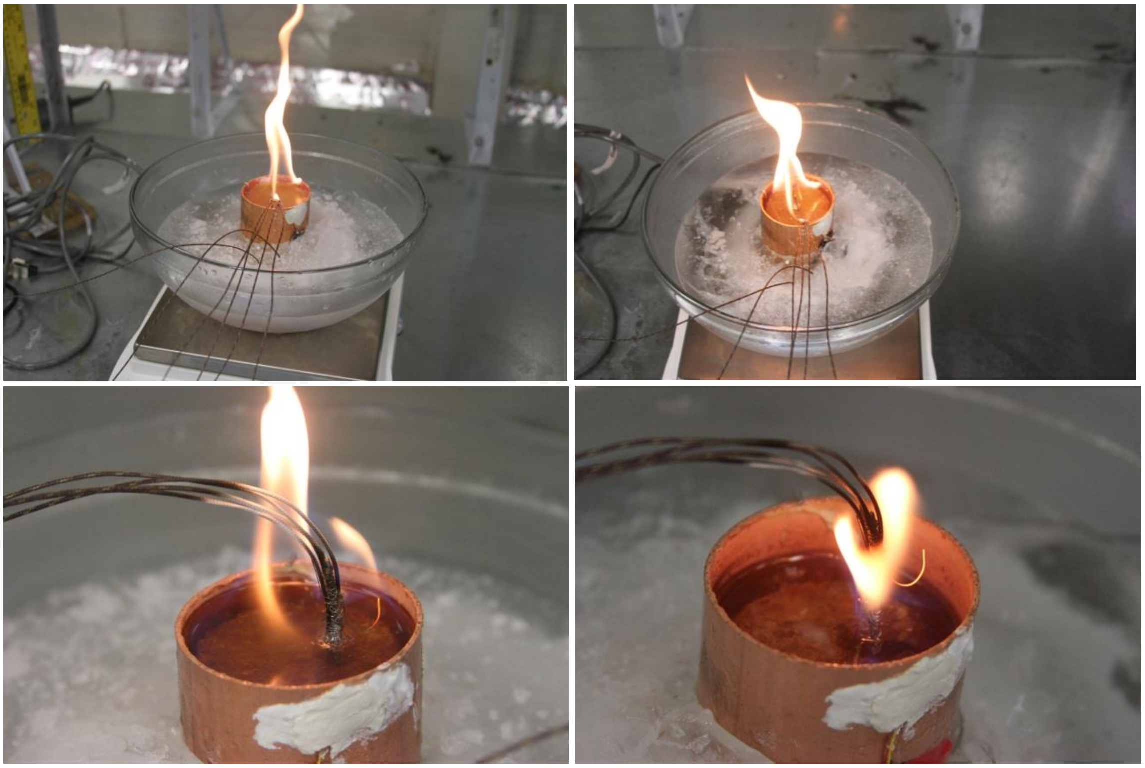


15 cm Container



Experiment Pictures

5 cm Container



10 cm Container

15 cm Container

Experiment Description:

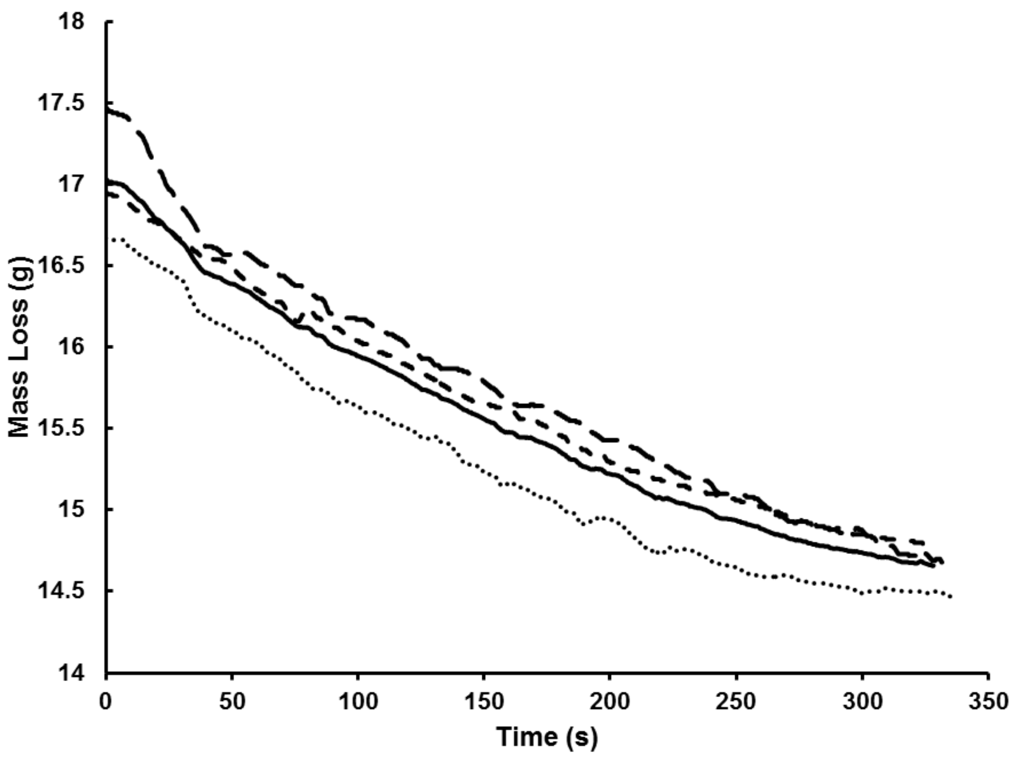
Weight ratio of oil to snow= 1:1

Snow packing density= 0.7 g/mL

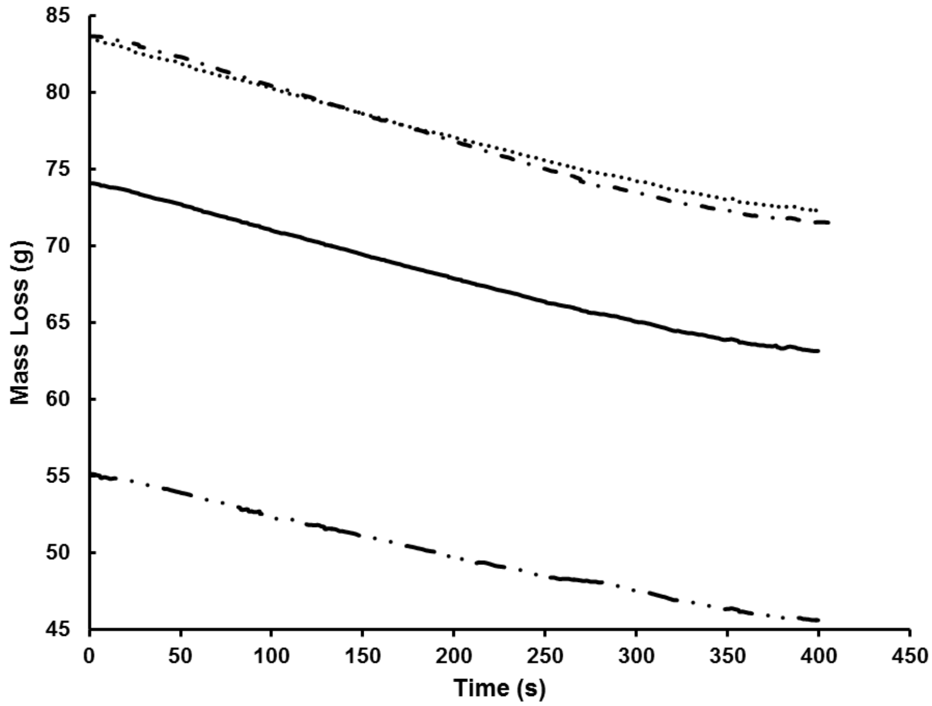
Mass Loss Vs. Time

Average
1st Trial
2nd Trail
3rd Trail

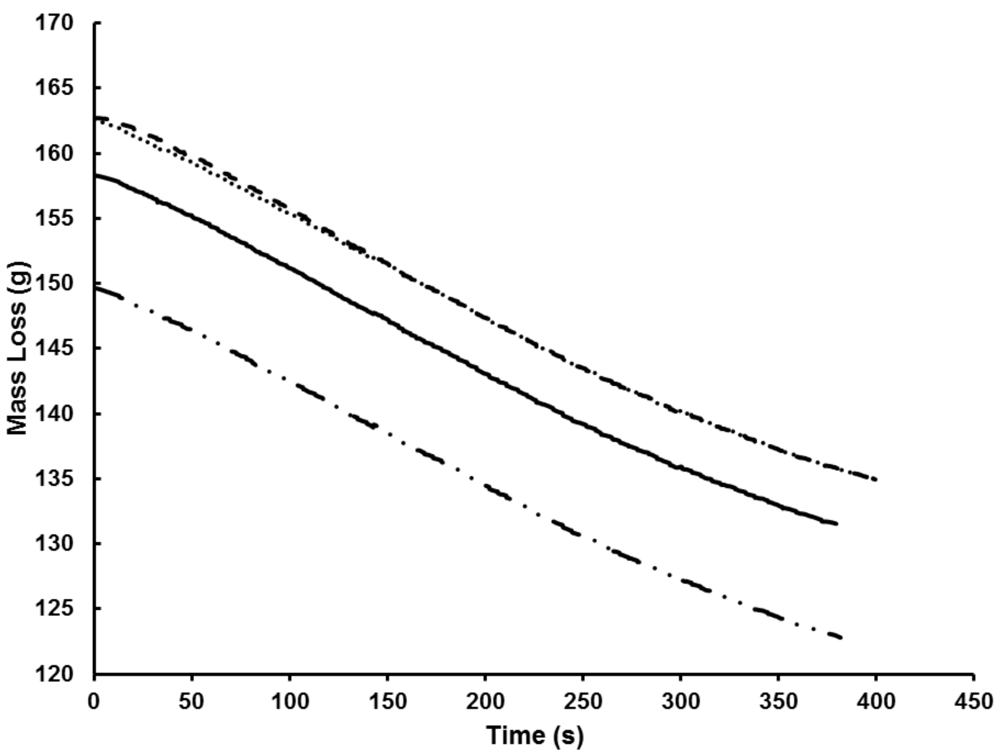
5 cm Container



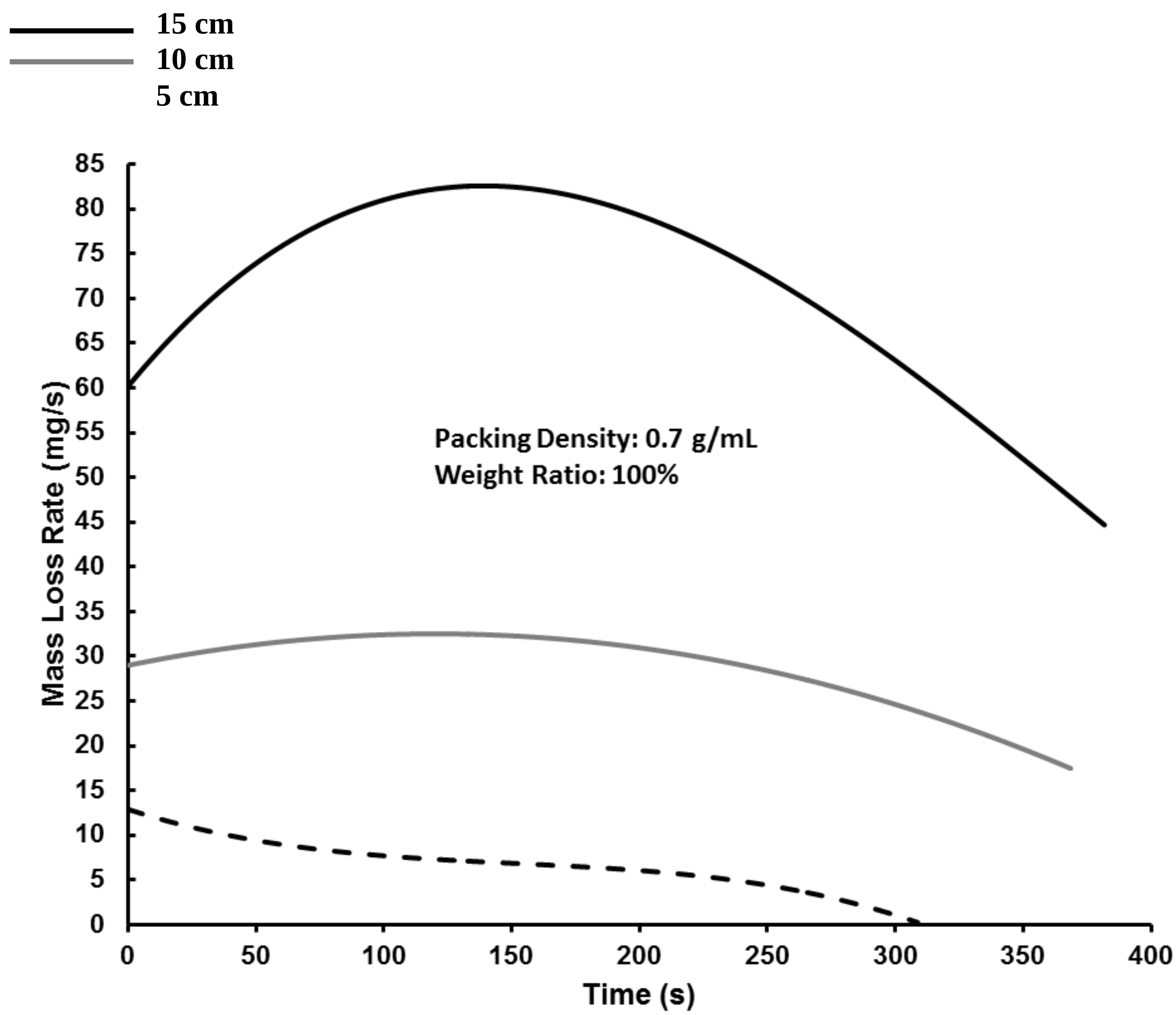
10 cm Container



15 cm Container

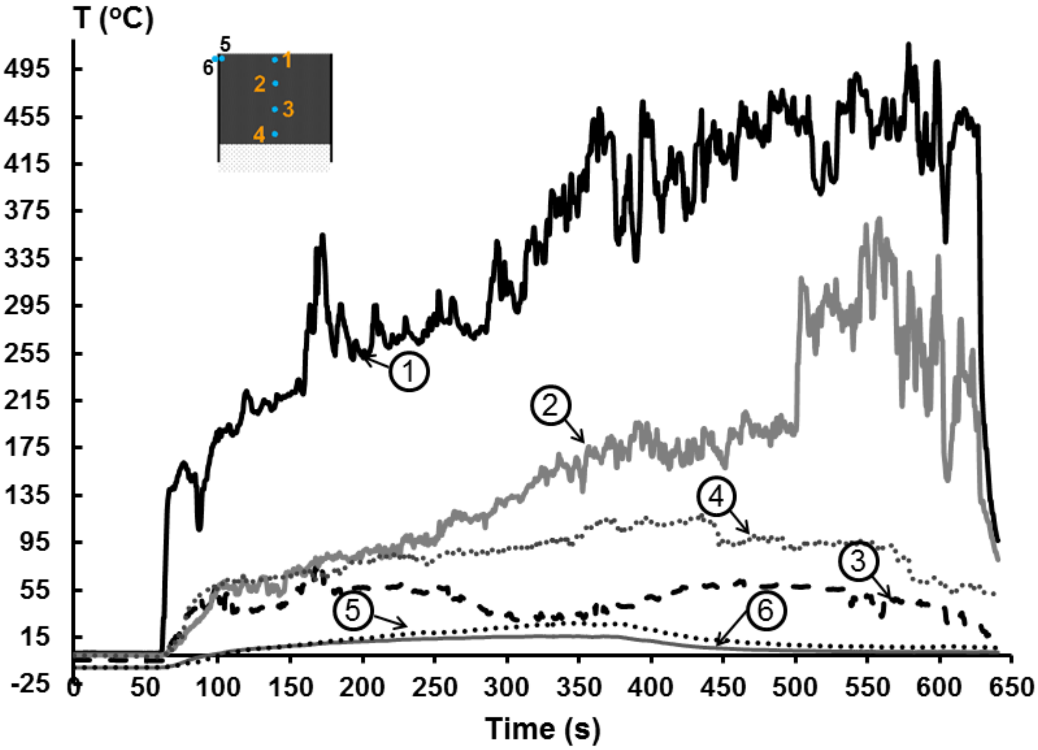


Mass Loss rate Vs. Time

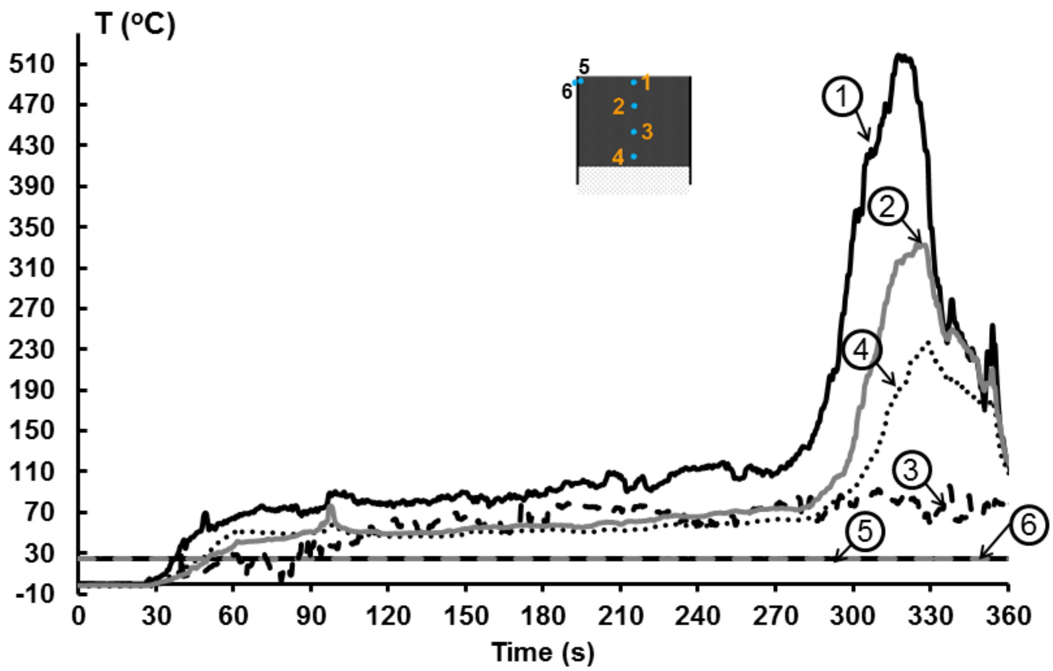


Temperature Vs. Time

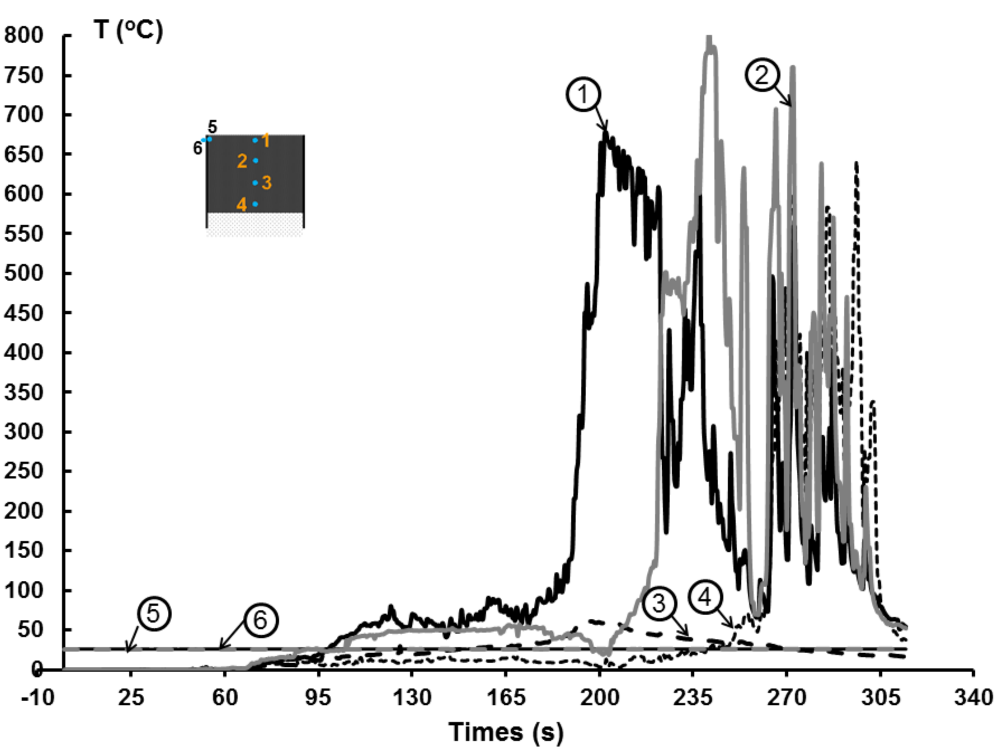
5 cm Container



10 cm Container

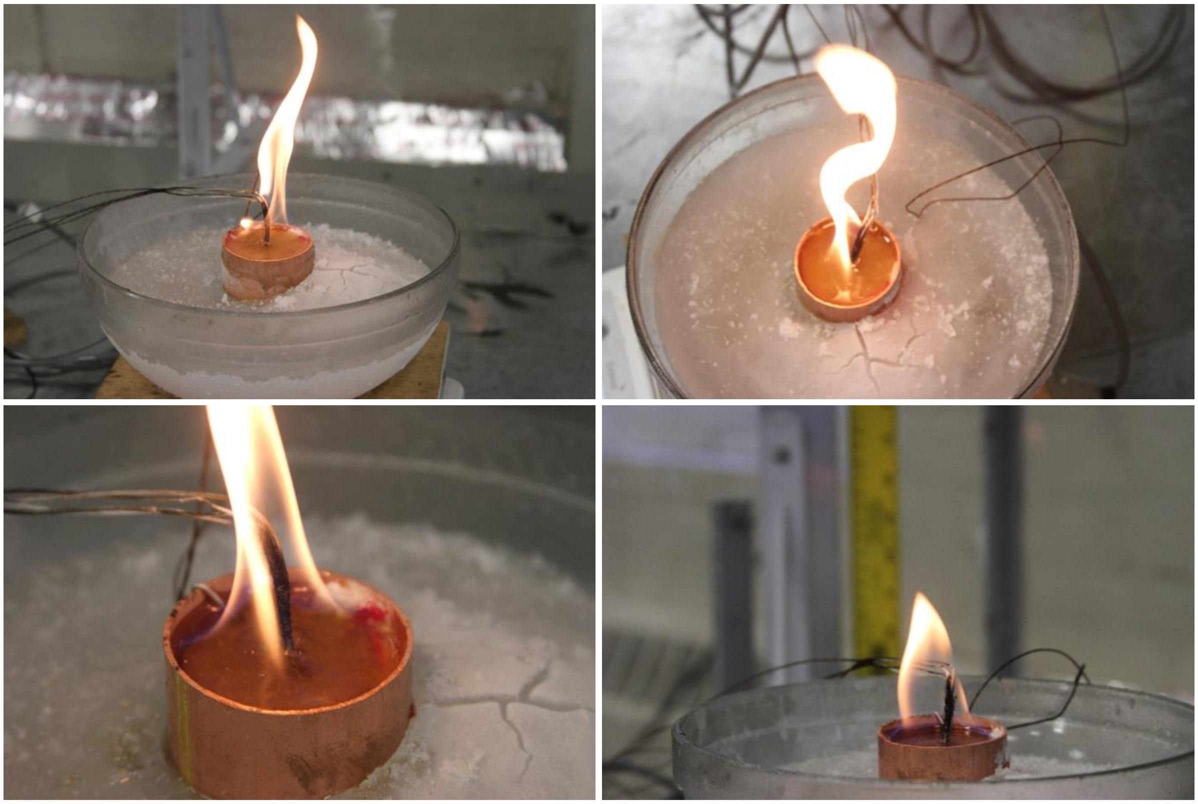


15 cm Container



Experiment Pictures

5 cm Container



10 cm Container

15 cm Container

Experiment Setup