# Experimental Study of Burning Behavior of N-heptane in Ice Cavities with Cross Air Flow

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## ABSTRACT

In situ burning (ISB) in the Arctic waters is a practical countermeasure to oil spill incidents, during which special ice cavity pool fires are naturally formed. However, most previous studies have focused on the burning of these fires in a quiescent environment. For the first time, the effect of cross air flow on burning behavior of ice cavity pool fires was experimentally revealed in the present study. Experiments were conducted by employing ice cavities of different depths (4, 6, and 8 cm) with the same diameter of 5 cm for various cross flow air speeds (0~1.5 m/s). It was found that the cross flow can significantly change the average mass loss rate (total burned mass over time). Three phases are identified in terms of the transient mass loss rate to characterize the burning behavior of n-heptane fuel: first, a slight decrease, then a continuous increase to reach a peak value and finally a rapid decrease until extinction. This behavior is different from that of the burning of pool fires in ice cavities in still air which has just two phases. In still air, the burning efficiency increased with the increase of the depth. With increase of cross flow air speed, the burning efficiency first increased then decreased with a maximum value at a wind speed of around 0.6 m/s. Asymmetric expansion of ice cavity in cross flow of air was quantified: the downstream expansion length is much larger than the upstream expansion length. However, the transverse-stream expansion length is almost identical to the upstream expansion length even with cross flow. The present study provides basic new data and understanding of burning behavior (burning rate, burning efficiency and ice cavity expansion) of ice cavity pool fire in cross flows, which is essential concerning ISB in Arctic regions with wind.

**KEYWORDS:** Ice cavity, pool fire, cross flow, mass loss rate.

## INTRODUCTION

In the Arctic waters, in situ burning (ISB) is a practical method of oil spill cleanup. In those harsh environment, deployment of traditional spill response equipment could be extremely difficult because of the ice coverage almost all year round. When the released oil is underneath the ice surface, it will gather at the bottom of the ice sheet then, once spring comes, the underneath hidden oil will be exposed and form melt pools of oil surrounded by ice walls [1-3]. Moreover, the remote places and harsh climate for oil exploration lack necessary infrastructure and support networks to stage a response for a large oil spill, so in situ burning could be the optimum solution.

Nowadays ISB has been widely applied and considered an effective technique which was successfully used to remove oil spills in the Deepwater Horizon accident [4, 5] and in ice-affected waters such as Alaska, Canada, and the Chinese Bohai Sea. There have been extensive efforts to

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understand the in situ burning of oil in cold regions since the 1960s [6-18]. Actually, most of these studies have been mainly focused on burning of oil in open waters [6, 7], the radiation fraction of heat back to the fuel surface [8, 9], burning rates [10-13], the burning efficiency [11, 14], boil over and other scenarios of burning on water [9, 15-17]. However, unlike burning of oil slicks on open water, burning of liquid fuel in an ice cavity presents unique physical characteristics.

Ice and oil can interact in many configurations of different sizes and shapes like channels and cracks between ice sheets or basins created naturally. Since there are no statistical data reported on the size and shape of ice cavities in Arctic regions, using a symmetric geometry will help to simplify the problem and facilitate modeling in a preliminary analysis of the practical situation. To support such analysis with experimental data, a series of experiments was conducted on oil fuel pool fires in different dimensions of cylindrical ice cavities. These were intended to mimic burns of liquid fuels for a better understanding of the burning of crude oil in icy conditions.

Experimental studies generally consider the situation of ISB in ice channels and cylindrical ice cavities of small size [19-24]. An earlier study by Bellino [19, 20] reported the burning behavior of crude oil in ice channels. A series of bench scale tests using a 100 cm long ice channel was conducted to study the effects of varying ice channel widths on the spread of an oil mixture. These experiments observed that the spread rates of oil in ice channels approximately follow a viscous two-dimensional box model. When the crude oil was ignited in an ice channel, the mass loss rate was primarily limited by ullage and fuel layer depth and less affected by channel width. When it comes to ice cavities, Farahani studied the mass loss rate and convection motion by conducting tests with crude oil [21], n-octane [22] and methanol [23] in different diameters (5 to 25 cm) of ice cavities. He found that due to the cavity expansion the average mass loss rate of crude oil in the ice cavity is greater than the mass loss rate in a pan, moreover, a physical model was developed to estimate mass loss rates. It was observed that a horizontal flow was induced by Marangoni effects near the surface following ignition. The detailed analysis of two dimensionless numbers (Marangoni and Rayleigh) was carried out by Farahani in n-octane pool fires. In the recent experiments of Shi [24], the burning behavior of large-scale crude oil fires in ice cavities varying from 5 to 125 cm diameters were studied. It was found that ullage is considered to be one of the important factors affecting burning efficiency. The optimum initial ratio of ullage to oil thickness would avoid the lateral cavity formation, which causes 7-23% of the crude to be trapped under the ice lip.

However, these previous studies only focused on the burning of oil in ice cavities in a quiescent ambient environment. When the pool fire in ice cavities is affected by wind, which is more practical in real outdoor conditions, it can be anticipated that the burning rates and behavior will change significantly due to the presence of the cross airflow, which will change the flame position and heat feedback considerably. Nevertheless, there are still no data reported to date on the burning behavior of ice cavity pool fires with cross airflows.

In the present study, experiments were carried out to investigate the burning behavior (burning rate, burning efficiency and ice cavity expansion) of heptane pool fires in ice cavities of various depths in cross airflows in a wind tunnel. The data were analyzed and discussed to have for the first time an understanding of these ice cavity pool fire behavior in wind.

## EXPERIMENTAL SETUP

Figure 1 depicts the experimental setup. The cross flow of air is provided by a wind tunnel with dimensions of 72 m (length) ×1.5 m (width) ×1.3 m (height). More details of the wind tunnel facility have been described in [25]. Out of concern that the relatively small size of the cross section might lead to possible flow constraints resulting in changes to the flow field near the pool fire and re-radiation effects from the tunnel boundary wall to the flame, thus affecting the burning behavior, the ice cavity was positioned just outside (0.3 m from) the outlet of the wind tunnel (Fig. 1) to eliminate such complex effects. The upstream cross flow air speed at the portal was monitored by a four-probe hotwire anemometer (accuracy: 0.01 m/s). Before the experiments, the wind velocity above the pool center was measured, and was assumed to be identical to that measured at the portal within such a small distance.

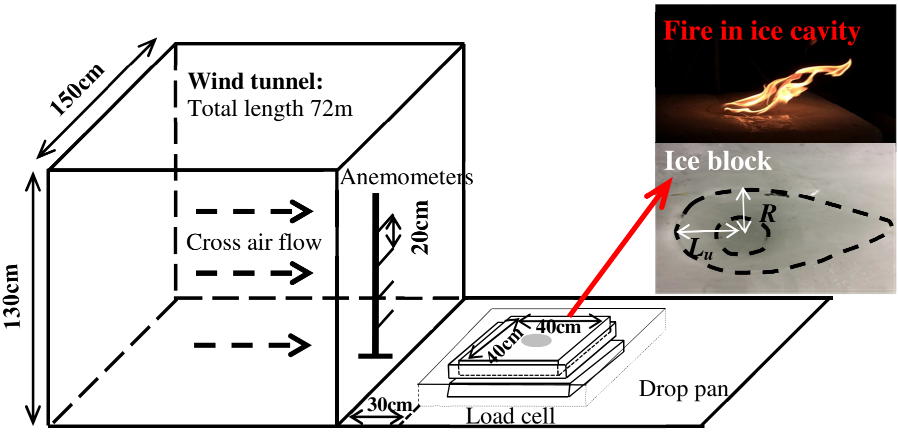


**Fig. 1.** Experimental setup.

An ice block (40 cm × 40 cm × 25 cm) with a cylindrical ice cavity having a 5 cm diameter hole excavated in its center was used (Fig. 1). The ice block was placed on a stainless steel pan which acted to capture any melted water on top of a load cell (0.01 g precision with sampling intervals of 1 s), which was used to record the transient mass throughout the experiments. The top surface of the ice block was flush with the floor of the wind tunnel. The gap between the pan and the ice block are around 3 cm to avoid the influence of airflow over the ice block. The cavity depths concerned were 4, 6, and 8 cm; and the cross flow air speeds were 0, 0.3, 0.6, 0.9, 1.2, and 1.5 m/s. Heptane was used as the fuel. The fuel was refrigerated before the test to obtain an initial temperature of around 2°C. A CCD camera (25 fps; 1440×1080 pixels) was employed to record the flame phenomena as well as the geometry of the ice cavity.

**Table 1. Experimental matrix**

| Diameter (cm) | Depth $H$ (cm) | $L$ (cm) | $V$ (ml) | Cross flow |
|---|---|---|---|---|
| 5 | 4 | 1 | 20 | 0-1.5 m/s |
| 5 | 6 | 1.5 | 30 | 0-1.5 m/s |
| 5 | 8 | 2 | 40 | 0-1.5 m/s |

Table 1 shows the initial ice cavity dimensions and fuel volumes used for each condition studied. For burning of the liquid fuels in an ice cavity, two possible extinction scenarios are involved: natural extinction and spillage of the fuel out of the cavity [21]. The depth ($H$) of the ice cavity and initial fuel layer thickness ($L$) shown in Table 1 were chosen based on the data obtained from preliminary tests to prevent spillage during combustion and thus to ensure that natural extinction happened in all experimental conditions. $D$ is defined as the diameter of cavity. Tests are conducted at room temperature 20 °C and with the ice temperature around 0 °C, respectively. In order to burn out naturally, the fuel was ignited immediately by a butane torch-igniter with an outstretched arm and the entire surface ignited within 1 s for all cases. All the experiments were repeated three times with averaged values used for further analysis. The loss due to water evaporation was assumed to be minimal and ignored [19, 21]. Fluctuation uncertainties are indicated as error bars in the data plots.

## RESULTS AND ANALYSIS

### Burning rate and burning efficiency

Differing from typical pool fires in a container (confined by sidewalls), the rigid walls of the pan are replaced by an ice wall and the dynamic environment created by the melting ice shows unique physical characteristics. The transport mechanisms are also significantly altered. After ignition, the surrounding ice walls and the cold water below the fuel layer form an effective heat sink, causing substantial heat loss. The release of heat from the flame and burning liquid fuel causes the surrounding ice to melt, resulting in a change in the geometry of the cavity thereby increasing the effective diameter of the fuel surface. The melting ice water flows to the bottom of the cavity, raises the fuel layer thus significantly reducing the ullage height (the distance from the fuel to the upper surface of the ice) at the same time. These unique dynamic changes (decrease in ullage height and widening of the burning area) are strongly coupled with the mass burning rate during continuous combustion.

Figure 2 presents the transient burning rate in three ice cavities with different depths, 4, 6, and 8 cm in still air. From Fig. 2, it can be observed that the burning behavior can be divided into two regimes according to the maximum transient mass loss rate which is consistent with the previous study [21]. For the first regime (starting at ignition), there is an initial increase in mass loss rate to reach a peak value. This phenomenon is mainly due to the increased effective diameter of the fuel layer due to the melting of the ice and widening of the cavity. the cavity widening process provides more burning surface area for the liquid and increases the mass loss rate. Moreover, this increased regime covers two parts, the initial self-sustained flame and the peak mass loss rate part, characterized by inefficient burning due to the deep lip of the ice cavity and limited air availability. The second regime is a rapid decline until extinction which is relatively short in duration (10–30% of total burning time) due to the significant heat loss in the fuel layer to the melting of cold water.

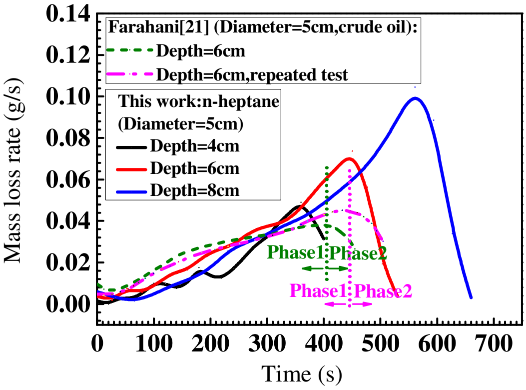


**Fig. 2.** The transient mass loss rate ( $\dot{m}$ ) measured for 5 cm diameter cavities in still air and comparison with [21].

Figure 3 shows the transient mass loss rate of the heptane fire in the ice cavity with the 4, 6, and 8 cm depths in different cross flow air speeds. Three phases are observed to characterize the burning behavior of the fuel layer in an ice cavity in wind condition: first, a slight decrease, then a continuous increase to reach a peak value and finally a rapid decrease until extinction. The three phases are divided according to the valley and peak value of the mass loss rate. It is noted that in still air, there could be also an initial slight decrease phase as can be seen in Fig. 2 by careful observation, however, it is of much shorter duration than that with a cross flow and can be negligible.

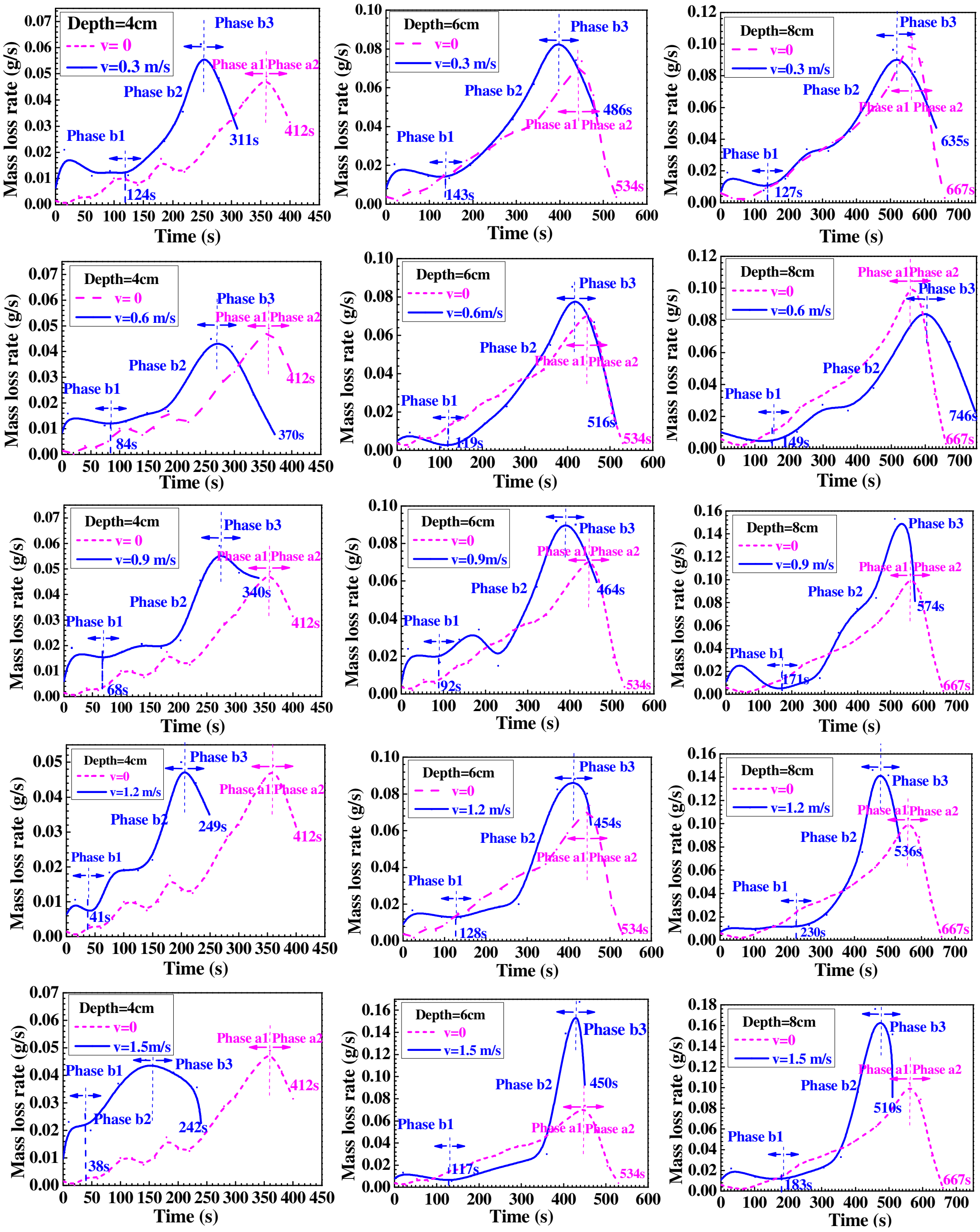


**Fig. 3.** The mass loss rate measured under various cross flow air speeds.

As shown in Fig. 3, all the experimental results in cross flow air start with an initial mass loss rate, with a value that is greater than that in still air, an effect that may be due to the enrichment of air in wind condition. Then the mass loss rate decreases gradually and reaches a minimum value at the end of phase 1, indicating the significance of convective heat loss in this phase when the fuel layer's temperature is low due to the weak flame at the initial development stage. The duration time to reach a minimum value decreases with the increase of cross flow air speed for the depth of 4 cm, however, the trend for 8 cm depth is contrary to the 4 cm case, except at the maximum cross flow air speed of 1.5 m/s. It is possible that the convective heat loss effect tends to overpower the widening process at this stage due to increase of the depth. For the depth of 6 cm, the burning duration time mentioned above decreases when the flow speed is less than 0.9 m/s, then increases at 1.2 m/s and slightly decreases at 1.5 m/s. In phase 2, the continuous increase of $\dot{m}$ is mainly caused by the fact that the diameter expansion increases the fuel surface area due to ice melting. The dependence on $D$ here in the process of continuous burning plays a relatively important role in the enhancement of $\dot{m}$ due to the cross air flow. The rapid decline to extinction in phase 3 is due to the significant heat loss from the fuel layer [21]. The fuel layer can act as an insulation, which can reduce heat loss to the cold water underneath effectively. As the fuel layer becomes thinner, there is more conduction heat loss that makes the temperature of the oil surface drop below its fire point and finally leads to flame extinction. Convection losses may also play a role at this stage.

Figure 3 shows that, when the wind speed continues to increase, especially in the comparison of 1.2 m/s and 1.5 m/s, the increase of mass loss rate is significantly faster than that in the absence of wind, and the time to reach the maximum mass loss rate is shorter than when there is no wind. This is because the heat flux from the flame melts the ice walls dramatically. The flame leans toward the ice surface due to cross air flow thus heating the downstream ice wall more efficiently. At the same time, the cold ice water at the bottom is gathering faster and raises the fuel layer thereby reducing the ullage quickly, which brings in a more effective burning of the fuel.

Table 2 and Fig. 4 show the average mass loss rate $\dot{m}$ (the total burned mass over the duration time) of n-heptane fires in the ice cavity for various cross flow air speeds. It is shown that, with the increase of cross flow air speed (0-1.5 m/s), the average mass loss rate $\dot{m}$ first increases and then decreases with a maximum value at 0.9 m/s. For a depth of 4 cm, the average mass loss rate $\dot{m}$ increases from 0.019 to 0.03 g/s in the cross flow air speed range of 0-0.9 m/s, then decreases to 0.026 g/s as the flow speed is 1.2 m/s and remains stable with further increase of cross flow. Similar trend appears at the other two depths.

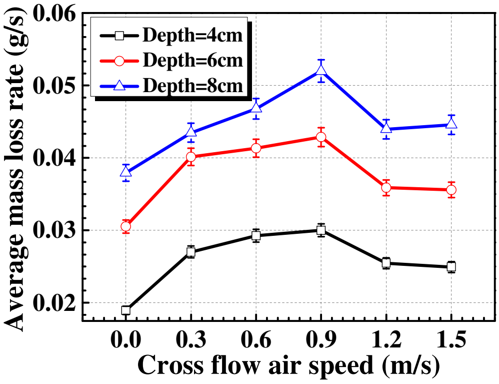


**Fig. 4.** Average mass loss rate at different cross flow air speeds.

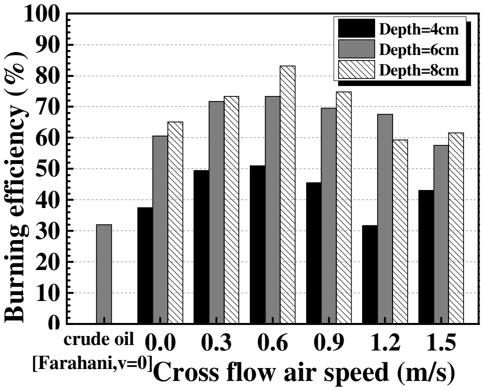


**Fig. 5.** Burning efficiency at different cross flow air speeds.

Cross flow can effectively promote burning by enhancing convection feedback to the fuel surface [26]. However, further increase of cross flow leads to more convective heat loss and less radiative heat feedback due to the decrease of view factor, meanwhile the combustible gas is blown away due to the cross flow of air. From Fig. 4, it can also be found that the average mass loss rate increases with initial depth of the ice cavity, which is due to the fact that the larger depth can remarkably reduce the heat loss through the water underneath the fuel layer.

**Table 2. Average burning properties of n-heptane in different cross flow air speed**

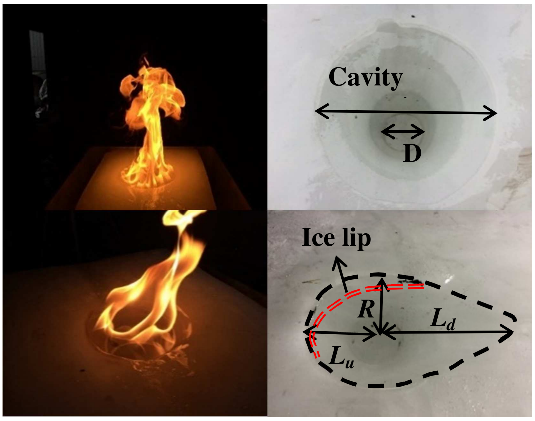
| Depth, $H$ (cm) | Flow (m/s) | $\dot{m}$ (g/s) | $\dot{m}''$ (g/(m$^2$·s)) | Efficiency (%) |
|---|---|---|---|---|
| 4 | 0 | 0.019 | 0.87 | 38 |
| | 0.3 | 0.027 | 1.45 | 49 |
| | 0.6 | 0.029 | 2.95 | 51 |
| | 0.9 | 0.03 | 1.61 | 46 |
| | 1.2 | 0.026 | 0.71 | 32 |
| | 1.5 | 0.025 | 1.10 | 43 |
| 6 | 0 | 0.03 | 1.17 | 61 |
| | 0.3 | 0.04 | 1.71 | 72 |
| | 0.6 | 0.041 | 2.07 | 73 |
| | 0.9 | 0.043 | 1.69 | 70 |
| | 1.2 | 0.036 | 1.03 | 68 |
| | 1.5 | 0.035 | 1.26 | 58 |
| 8 | 0 | 0.038 | 1.13 | 65 |
| | 0.3 | 0.043 | 1.25 | 73 |
| | 0.6 | 0.047 | 1.96 | 83 |
| | 0.9 | 0.052 | 1.66 | 75 |
| | 1.2 | 0.044 | 0.93 | 59 |
| | 1.5 | 0.045 | 1.07 | 62 |

Figure 5 presents the burning efficiency defined as the ratio of burned fuel mass to initial value. In still air, the burning efficiency increased from 38 to 65% with the increase of depth. With the increase of the cross flow air speed, the burning efficiency increased to a maximum value at 0.6 m/s; then decreased as the air speed was further increased. The burning efficiency is generally higher with a cross flow than in still air. This means that the cross flow of air can improve burning efficiency to some extent; however, it must be pointed out that this may be only the case for the range of small size of ice cavity considered here.

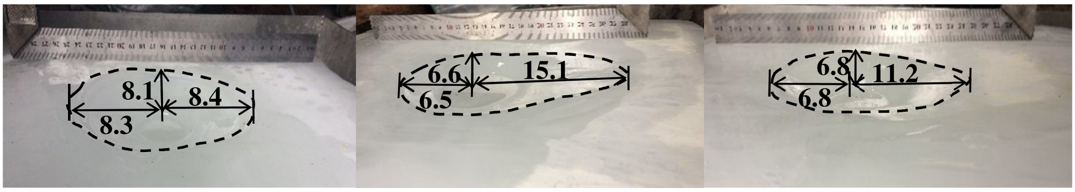
### Geometry change of ice cavity

It has been reported that one of the major factors affecting the burning rate and efficiency of a liquid fuel is the continuous change of the ice cavity geometry during combustion [21]. Figure 6 shows the change in the cavity geometry and labels the relevant dimensions associated with the geometry changes. During the burning of the n-heptane pool, the ice walls of the cavity were melting and the diameter of the cavity was constantly increasing.

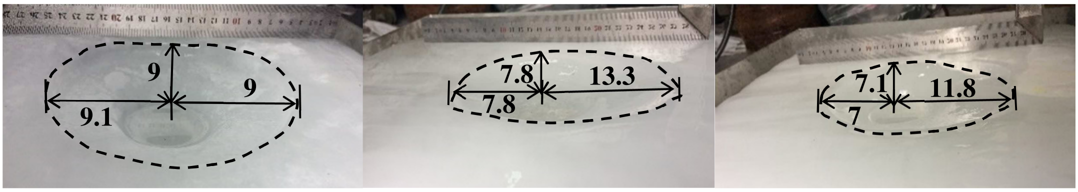
As shown in Fig. 6 (a), unlike the behavior in still air, it can be seen that due to the cross flow there is significant asymmetric expansion of the ice cavity. The unique formation of an “Ice lip” (lateral cavity) phenomenon can still be observed in the cavities on the windward side. Here, we can define the three lengths that form the ice cavity expansion in cross flows, the upstream ($L_u$), downstream ($L_d$) and transverse-stream ($R$) expansion length, as shown in Fig. 6 (a). Representative values of these lengths in various cross flow air speeds are shown in Fig. 6 (b). It could be seen that in no cross flow the three lengths are similar due to nearly axi-symmetrical expansion of the cavity. However, when subject to a cross flow, the upstream expansion length decreases, while the downstream expansion length increases with air flow speed. Meanwhile, the transverse-stream expansion length ($R$) seems to be still similar to the upstream expansion length even with a cross flow.



(a)



4 cm 0 m/s | 4 cm 1.2 m/s | 4 cm 1.5 m/s

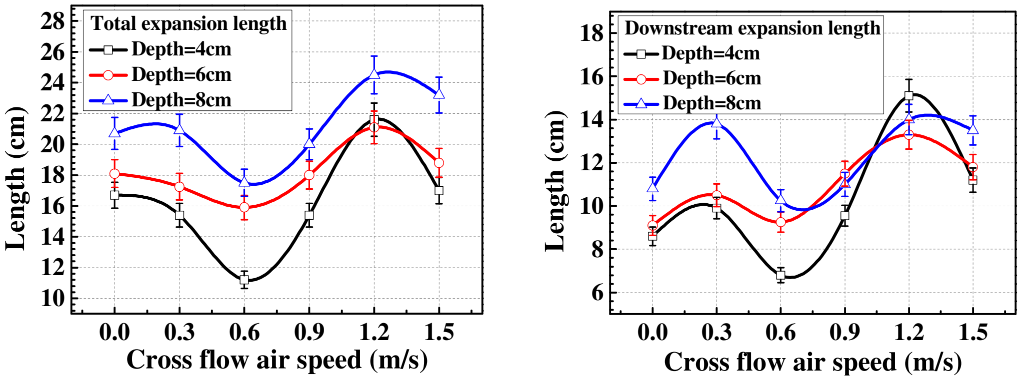


6 cm 0 m/s | 6 cm 1.2 m/s | 6 cm 1.5 m/s

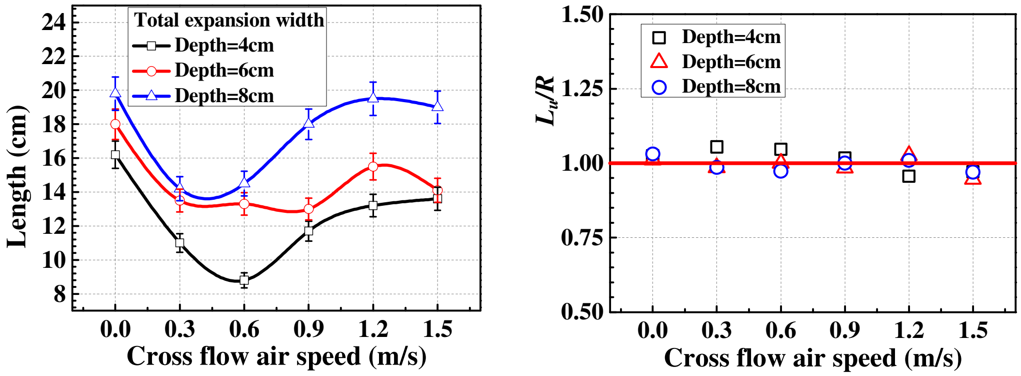
(b)

**Fig. 6.** The final cavity expansion lengths (unit: cm) at different cross flow air speeds.

Figure 7 presents quantitatively the total expansion length ($L_u$+$L_d$), the downstream expansion length ($L_d$), the total transverse-stream expansion length (2$R$) as well as the ratio of upstream expansion length to the transverse-stream expansion length ($L_u/R$) measured at various cross flow air speeds for different cavity depths. It can be observed that: (1) the total expansion length decreases to a lowest value at 0.6 m/s, then increases to a maximum value at 1.2 m/s finally decreases again, Fig. 7 (a); (2) the downstream expansion length (Fig. 7b) has another increase regime from 0-0.3 m/s compared with the total expansion length; (3) the transverse-stream expansion length first decreases, then increases and finally almost keep constant (Fig. 7c); and (4) the upstream expansion length is almost equal to the transverse-stream expansion length (Fig. 7d).



(a) total expansion length ($L_u$+$L_d$) (b) downstream expansion length ($L_d$)



(c) total transverse-stream expansion length (2$R$) (d) $L_u$ /$R$

**Fig. 7.** Cavity expansion dimensions at different cross flow air speed.

## CONCLUSIONS

Experiments were conducted to reveal the effect of cross air flow on burning behavior of ice cavity pool fires starting with a range of small sizes for the ice cavity, and by employing ice cavities of different depths at a constant diameter of 5 cm. Major findings include:

With increase of cross flow air speed (0-1.5 m/s), the average mass loss rate first increases and then decreases with a maximum value at 0.9 m/s. Three phases are identified according to transient mass loss rate to characterize the burning behavior of fuel in an ice cavity with cross flow of air: first, a slight decrease, then a continuous increase to reach a peak value and finally a rapid decrease to extinction. This behavior is different from that in still air which has just two notable phases.

In still air, the burning efficiency increases with the increase of the cavity depth. With increase of cross flow air speed, the burning efficiency first increases then decreased with a maximum value at around 0.6 m/s. Asymmetric expansion of the ice cavity in cross flow of air is observed: the downstream expansion length is much larger than the upstream expansion length. However, the transverse-stream expansion length is almost identical to the upstream expansion length even with cross flows.

The present study provides basic new data and understanding of burning behavior of ice cavity pool fires in cross flows, which is essential concerning ISB in Arctic regions with wind. However, it could be noted that the problem is very complicated due to the presence of wind (cross airflow) in real outdoor conditions concerning ISB. The present experiments and observations are still limited by the current fire size and ice cavity sizes. It could be interesting potential work to explore larger size fires in the near future to confirm the generalization of the observations in this study. In addition, different types of fuels, specific temperature and larger wind speeds found in an arctic environment definitely warrant future study.

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