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Convection-driven cavity formation in ice adjacent to externally heated flammable and non-flammable liquids

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ABSTRACT

A parametric experimental study on melting of ice adjacent to liquids exposed to various heat fluxes from above was conducted in order to understand the role of liquid properties in formation of cavities in ice. In previous experiments related to in situ burning (ISB) of crude oil contained in ice, the convective motion in the fuel layer was identified as a key parameter determining the amount of the ice melting. An experimental setup was designed to measure the melting rate of the ice and penetration speed of the liquid similar to the lateral cavity formation problem observed in ISB experiments. Lateral cavity formation is identified as a key factor reducing the removal efficiency of ISB. The experiments were conducted in a transparent glass tray (70 mm × 70 mm × 45 mm) with a 20 mm thick ice wall (70 mm × 50 mm × 20 mm) placed on one side of the tray. Liquids in the tray (water, n-pentane, dodecane, n-octane, m-xylene, and 1-butanol) that were adjacent to the ice wall were exposed to varying heat fluxes mimicking flame heat feedback from a pool fire. The results of ice melting rate among different liquids were found to vary significantly. The exposure of the liquids to the radiative heat flux led to temperature difference between the liquid and the ice, thereby creating a heat transfer pathway towards the ice that provided the required energy for the melting. It is suggested that Marangoni-driven convection caused by the temperature gradient near the ice and below the free surface of the liquid is influential in the ice melting. A scaling analysis of the surface flow was undertaken to elucidate the influence of surface tension effect (Marangoni convection). It was found that the surface flow velocity obtained from the surface tension effect at the liquid free surface correlates well to the melting front velocity.

1. Introduction

The cleanup of oil spills in the Arctic offshore is a more complicated practice compared to cleanup in open waters as the fate and behavior of oil is significantly affected by the presence of ice (Fingas and Hollebone, 2003). The technical difficulties brought upon by the adverse weather conditions and presence of ice in the Arctic impede the conventional methods of cleanup (Glover and Dickins, 1999). However, controlled in situ burning (ISB) has proved to be an effective measure for oil spills in ice conditions and has been used successfully to remove oil from spills in ice-affected waters (Buist et al., n.d.). Although there has been numerous studies addressing the effectiveness of ISB, the interaction of oil and ice before and during burning has for the most part been neglected.

One likely configuration of oil and ice is the appearance of the oil on solid ice, such as those created in the spring by vertical migration from an encapsulated oil layer (Potter and Buist, 2008). Combustion of the oil slick in such situations melts the ice in the immediate vicinity of the oil and creates lateral cavities in the ice when oil surface is below the ice. The geometry change of ice by lateral cavities alters the burning behavior of the oil slick (Bellino et al., 2013; Shi et al., 2016). The burning behavior is affected by both the cold ambient and the geometrical variation in ice caused by the melting. In particular, expansion of the burning area further reduces the slick thickness, which will cause early extinction of the ISB process (van Gelderen et al., 2015). The melting will also allow a portion of the oil to reside in the lateral cavity, thus preventing the exposure of air to the trapped oil, and potentially reducing the burning efficiency of the ISB method (Shi et al., 2016). The decrease in the burning efficiency translates to larger amount of oil residue (unburned oil and burned oil residue). In addition, the confined residue in the cavity would be harder to collect, and, if it stays

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untreated, it could be encapsulated due to freezing of the water in colder seasons. Thus, based on the above, it is clear that further understanding of the ice melting is important to assess the effectiveness of ISB as an oil spill response method in environments that involve ice.

Ignition and combustion of the oil adjacent to ice bodies create horizontal temperature gradients on the oil surface because of the proximity of ice and flames (Farmahini Farahani et al., 2014). Liquids with an imposed temperature gradients on their upper free surface show a mechanical instability, giving rise to subsurface flows that is known as Marangoni or thermocapillary convection (Normand et al., 1977). As temperature differences increase, the Marangoni effect becomes more pronounced in the liquid. When the surface tension coefficient of a liquid is negative, the flow is driven from hot regions to colder ones (Yu et al., 2015). This type of flow has been studied due to its practical applications in crystal growth, welding, and flame spread of liquid fuels at their sub-flash temperatures (Pimputkar and Ostrach, 1981; Polezhaev, 1984; Ross, 1994). In particular, the surface tension convection (also known as thermocapillary convection) is found to be the main mechanism attributing to the subsurface flow in flame spread over liquid fuels while the effect of the buoyancy is smaller (Li et al., 2015; Takahashi et al., 2008).

The thermocapillary convection is also influential in the ice melting during burning of liquid fuels adjacent to the ice walls (Farmahini Farahani et al., 2015; Farmahini Farahani et al., 2017a; Farmahini Farahani et al., 2017b). These previous studies showed that the enhanced melting of the ice in contact with fuel layer, known as lateral cavity formation, is a result of convection in the liquid phase. In particular, thermocapillary flow due to surface tension gradients were found to be driving the convection (Farmahini Farahani et al., 2015; Farmahini Farahani et al., 2017a). In view of this, the melting rate of the ice should associate to the magnitude of the convective flows in the liquid fuel that are driven by the surface tension effect.

To evaluate whether such a relationship exists, a parametric study with different liquids exposed to heat flux from above were conducted. The objectives of this study are to experimentally evaluate the extent in which liquids with different thermophysical properties influence the melting of the ice when exposed to a heat flux from above. Also, a scaling analysis was performed to examine the possible correlation between the surface flow velocity in the liquid layer and melting front velocity of the ice. Crude oils are complex fuels with heterogeneous components that show distinctive burning behavior compared to single component fuels (van Gelderen et al., 1994). Because multicomponent fuels are so complex, they can introduce significant variability in experiments. Therefore, studies with pure fuels are important for high-fidelity laboratory experiments such as the current one that investigates the role of thermophysical properties of oils in ice melting. The results of this study can be applied towards improved guidelines of oil spill cleanup in the Arctic by better evaluation of the effectiveness of ISB adjacent to ice bodies.

2. Experimental procedure

2.1. Experimental setup

The experimental setup was developed to systematically study the cavity formation phenomenon that was observed and studied previously in experiments involving flaming combustion of a liquid fuel bounded by an ice wall (Normand et al., 1977; Farmahini Farahani et al., 2017a; Farmahini Farahani et al., 2017b). To provide a controlled environment, experiments on liquids with different thermophysical properties were conducted where they were exposed to different radiative heat fluxes to investigate the influential parameters on melting of the ice. The schematic of the experimental setup used in this study is shown in Fig. 1 (a). The tray used to contain ice and liquids was made of borosilicate glass (2 mm wall thickness) with outside dimensions of 70 × 70 mm and a depth of 45 mm. Each experiment used a 66 × 50 × 20 mm ice wall placed on one side of the vessel as shown in Fig. 1 (a) and (b). Liquids were refrigerated to a temperature of around 0 °C before they were poured into the glass tray. Fig. 1 (b) shows an image of the ice wall and liquid inside the tray. The ice wall was covered with an insulation shield during the experiments to protect the top section of the ice (the part above the liquid surface) from melting directly by the radiation of the cone heater (Babrauskas, 1984). Demineralized water was frozen using a directional freezing method to minimize the visual imperfections and reduce the inclusions of gas bubbles. A DSLR (100 mm focal length lens) was placed at an approximately 50 cm distance from the tray and directly facing the ice wall. The intrusion length along the ice wall was nearly constant, except for in the immediate vicinity of the glass wall (approximately 1–2 mm), where ambient temperature and contact to the glass tray enhanced the melting. Thus, the camera was focused on the mid-plane perpendicular to the ice wall for the intrusion length measurements. Images were captured with intervals of ten seconds to track the ice-liquid interface movement due to the melting.

Water, n-pentane, n-dodecane, n-octane, m-xylene, and 1-butanol, all were carefully chosen based on their thermophysical properties for number of reasons; 1) transparency of liquids to observe the melt front movement, 2) a relatively wide range of thermophysical properties to examine the influence of the various thermophysical properties on melting front velocity. Liquid thermophysical properties were obtained by commercial software (Aspen HYSYS™) and are reported in Table 1 in their SI units.

2.2. Experimental matrix

Table 2 presents the experimental matrix of the tests indicating the liquids and heat fluxes used in the experiments. The use of high heat fluxes was not possible due to low auto-ignition temperature of some of the liquids. Thus, only water was tested at 12 and 15 kW/m^2. All experiments were repeated three times to ensure the reproducibility of the results.

2.3. Uncertainty analysis

The experiments were initiated with heating of the cone to a desired temperature, which corresponded to a certain heat flux. The cone heater was calibrated to an accuracy of 5% with a water-cooled heat flux gauge (Schmidt-Boelter type). Then, the ice wall was placed in the tray and the liquid was added into the tray to a depth of 35 mm (with initial temperature of 0–2 °C). The ice walls were carefully sized to uniform thickness of 20 mm by a ruler with accuracy of 1 mm. To start the experiments the radiation shield of the cone heater was removed to expose the liquid to the incident heat flux. The fuel layer melted the ice and created a void in the ice wall that eventually led to the splitting of the ice wall. The splitting was defined to be the end point of the experiments and was recorded with accuracy of 3 s. All images taken from the experiments were processed via ImageJ (Schneider et al., 2012) to track the ice-liquid interface and create the melting profile of the ice wall. To convert pixels to the length unit, a ruler with 1 mm accuracy was placed at the focal point of the camera as the calibration target before each test. The melting profiles were used to obtain the changes in length and width of the lateral cavity during each test. This is further explained in Section 3.1. In addition, the ice wall mass was measured before and after each experiment to obtain the amount of melted ice and the melting rate. The largest possible error for melting front velocity based on uncertainty of length and time measurements was 7%.

3. Results and discussion

3.1. Cavity profiles

The experiments started with exposing the liquids to a certain heat