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Experimental study of burning behavior of large-scale crude oil fires in ice cavities

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ABSTRACT

In situ burning (ISB) on open water can remove more than 85–90% of spilled oil making it a promising technology for an efficient oil spill response. The current study examines the burning behavior of an oil spill in the presence of ice, comparable to the Arctic environment. Alaska North Slope (ANS) crude oil with initial thickness varied from 0.5 to 1.5 cm in ice cavities with effective diameters of 28 and 110 cm and depths of 10–25 cm are studied. The experiments show that, overall, the average burning rate in an ice cavity is greater than that of a similar sized vessel or a pan. However, overall efficiency is much lower compared with ISB on open water. This is because of oil layer penetration horizontally into the ice, forming a pocket or a lateral cavity. Depending on initial conditions such as ullage, geometry of cavity and thickness of oil layer, 7–23% of the oil is trapped within the lateral cavity and thereby un-recoverable. The broader implications of the experimental results towards ISB in the Arctic are discussed.

1. Introduction

Although the successful use of ISB during the Deepwater Horizon oil spill response in 2010 [1] has increased the interest of this countermeasure technique for oil spills, its use is not new and has proved effective for massive oil spills on open water [2]. Great efforts have been devoted to understand the burning behavior of crude oil on water since 1976. These efforts include studies of the flame temperatures of burning oil slicks on water [3,4], the radiative fraction of heat back to the fuel surface [5,6], the steady state burning rates of small and large slicks [7,8], the effect of oil slick thickness on the burning rate [8–10], and the burning efficiency [8,11]. Boilover burning of thin oil slick on water [6,9,12] and the heat transfer modeling for oil slick burning on water have been conducted [10,13–15]. Modeling of emulsion formation for oil spill on open water has also been studied [16].

ISB has been considered as a primary spill response for oil spills in ice-affected water since the 1970s. It has been used successfully to remove oil spills in ice-affected waters in Alaska, Canada and Scandinavia. But serious consideration of intentionally using ISB began in the early 1980s. When an oil spill occurs under icy conditions in the Arctic, the presence of ice, ice channels, and ice slurries causes changes in both the spread and burning behavior of the oil [17]. ISB may be the simplest, quickest, and most efficient methodology for clean up. The remoteness and harsh climate in the Arctic make it difficult for immediate use of heavy machinery to simplify either the mechanical recovery or the use of dispersants, which are the two other primary response methods for marine oil spill cleanup. Many field trials have been conducted to examine and document burning of spilled oil on solid ice, in snow and in broken ice. Early studies showed the ignitability and burning efficiency (> 80%) of oil on ice without containment and promoter [18,19]. A large experimental spill study in the Beaufort Sea [20], carried out in 1981, showed 90% burn efficiency with a 1 mm/min average burning rate in small pool slicks. In the spring of 1982, oil from an experimental spill under the landfast sea ice in Alaska was burned after it was released and rose to the surface [21]. An estimated removal efficiency of 95% was reported. The burning of emulsions and weathered oil in melted pools was also studied [22–25]. Work related to oil spill on snow and in broken ice, brash and frazil ice was reported in [26,27], with the most up-to-date reviews being in [28,29].

Although the field studies documented the burning rate and efficiency in icy conditions, they provide limited fundamental analysis or physical explanation of the controlling parameters related to the burn rates and efficiencies. A laboratory scale study of a mixture of motor oil and petroleum oil (3:1) burning in ice channels was reported [30]. A formation of lateral cavity named

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“ice lip” was observed for the first time in this work, which was similar to the fissure formation during lava flow because of lava melting the ground [31]. The burning behavior of Alaska North Slope (ANS) crude oil in cylindrical ice cavities was investigated at a laboratory scale for cavity diameters between 5 and 25 cm [32]. The formation of a lateral ice “lip” was observed in this study as well. It was also found that the burning rate of crude oil in ice cavities are greater than in confined vessels, because of the pool expansion (geometry change because of melting ice). However, the geometry change of cavities for larger sizes and its influence on the burning rate and efficiency have not been investigated. The focus of this study is to explore the burning behavior of ANS crude oil in pools with effective diameters larger than 25 cm and the influence of geometry change due to the melting of the ice.

2. Experimental setup and procedure

To simulate ANS burning behavior for spilled oil in ice cracks and large melted ice pools, a 65×16 cm^2 ice channel and a 1.1×1.1 m^2 square ice cavity were constructed.

2.1. Ice channel

Fig. 1 shows the experimental setup of the ice channel. A 65 (length) × 16(width) × 10(depth) cm^3 channel was carve out of a $110\times53\times25$ cm^3 ice block. A set of water cooled total heat flux gauges (Medtherm 64 series, gardon gauge) with measuring ranges of 0–22 kw/m^2 and 0–56 kw/m^2 were used to study the heat flux emitted by the flame. One heat flux gauge (gauge 1 in Fig. 1) was placed on the short edge of the ice block, which was 55 cm away from the center of channel and 19 cm above the initial oil surface. Three heat flux gauges (gauges 2–4 in Fig. 1) were placed at the long edge of the ice block, which were 59 cm away from the center of channel and 39, 89 and 139 cm above the initial oil surface. Crude oil was poured into the channel to form 0.5, 1 and 1.5 cm thick oil layers (see Table 1 for the corresponding oil quantities). The different oil thicknesses allowed studying the influence of ullage (driving the air entrainment rate at the base of the fire) and oil quantity on the burning behavior. The maximum thickness of 1.5 cm was chosen to prevent overflow during the burn, based on the test results with smaller sizes [32].

Oil was ignited by a butane torch with an extended arm and was allowed to burn out naturally. Two video cameras were placed along the long and short edges (labeled as video camera 1 and 2 in Fig. 1) to record the burning. 3 M oil-only absorbent pads were used to collect the remaining oil (heavy component residue) after the burn. The average mass burning rate and burning efficiency (ratio of mass of burned oil to initial value) were obtained by weighing the absorbent pads before and after the clean up. The mass burning rate as a function of time was not recorded, because of limiting load cell capacity. Two repeated test trials were conducted for each oil thickness.

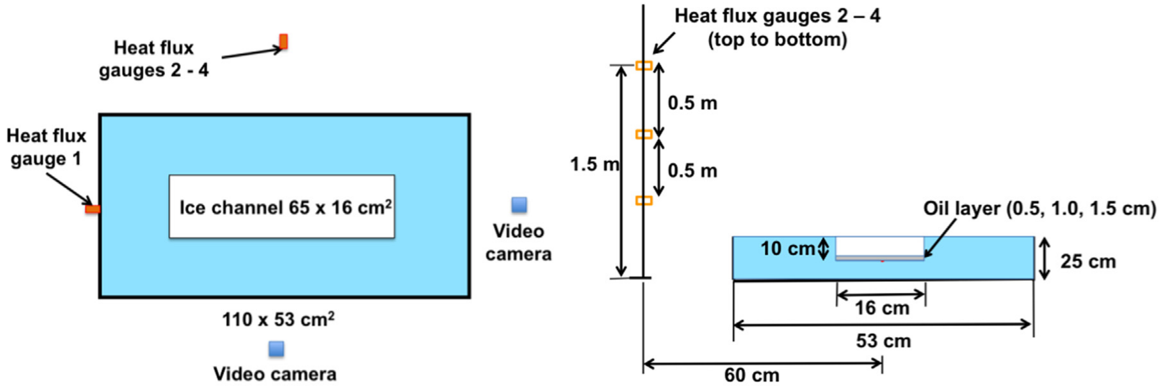
Table 1
Three selected oil thicknesses with their corresponding oil quantities.

Oil thickness (cm)	Oil quantity (g)
0.5	500
1	800
1.5	1275

2.2. Square ice cavity

Fig. 2 shows the experimental setup consisting of a 3 m(L) × 3 m(W) × 0.3 m(H) outer frame made of plywood wrapped with two 5×6 m^2 fire-resistant and waterproof sheets. Sixteen carving ice blocks, each $1\times0.5\times0.25$ m^3 and 136 kg (300 LB), were placed around the perimeter of the container, leaving a 1.1×1.1 m^2 area at the center with a cavity depth of 0.25 m. The ice blocks were fused together to prevent the oil from spreading into the gaps during the burn. A layer of water (~3 cm) was added into the cavity to prevent the oil from spreading underneath the ice blocks.

Two thermocouple trees were placed inside the cavity, one at its center and another adjacent to the wall (see Fig. 2), to measure the temperature distribution in the liquid and record the motion of the liquid layer. K-type glass sheathed thermocouple (Omega, GG-K-30-SLE) with wire diameter of 0.25 mm and maximum temperature of 482 °C was used and was welded to produce a measuring junction (bead) by an Omega thermocouple welder (TL-WELD). The thermocouples were supported by two separate 27 cm long metal frames. Each thermocouple was inserted into a ceramic insulating tube (1.6 mm inner diameter), leaving only the bead exposed (5 mm from the tip of the ceramic tube). It was then fastened to the metal frame using thermocouple cement. Thermocouple wires passed beneath the ice blocks to a data logger located 5 m away from the pool centerline. Fig. 3 shows the spacing of the thermocouples along the pool centerline and the initial location of the oil and water layers. Initially, thermocouples C19 to C21 were immersed in the liquid oil and water, respectively, while C20 was placed at the oil and water interface. C18 was few millimeters above the initial oil surface. Thermocouples C17 to C0 were placed all the way to the top of the cavity. After ignition, water from the melting ice collected at the bottom of the cavity and



(a) Top view (b) Side view

Fig. 1. Experimental setup for oil burns in an ice channel. (a) Top view, (b) Side view.