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Effectiveness of a chemical herder in association with *in-situ* burning of oil spills in ice-infested water

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ABSTRACT

The average herded slick thickness, surface distribution and burning efficiency of a light crude oil were studied in ice-infested water to determine the effectiveness of a chemical herder in facilitating the *in-situ* burning of oil. Experiments were performed in a small scale (1.0 m^2) and an intermediate scale (19 m^2) setup with open water and 3/10, 5/10 and 7/10 brash ice coverages. The herded slick thicknesses (3–8 mm) were ignitable in each experiment. The presence of ice caused fracturing of the oil during the herding process, which reduced the size of the herded slicks and, as a consequence, their ignitability, which in turn decreased the burning efficiency. Burning efficiencies relative to the ignited fraction of the oil were in the expected range (42–86%). This shows that the herder will be an effective tool for *in-situ* burning of oil when the ignitability issues due to fracturing of the oil are resolved.

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1. Introduction

One of the oil spill response methods associated with oil spill preparedness in the Arctic environment is *in-situ* burning, *i.e.* burning the oil from the water surface (Buist et al., 2013; Nuka, Research & Planning Group, LLC, 2010). *In-situ* burning is suitable for the Arctic as it can be used in ice-infested waters and it can remove up to 99% of the oil from the water surface (Potter, 2010a; Guénette and Wighus, 1996). In principal, *in-situ* burning can be applied to oil slicks on water of any oil type and slick size as long as the oil can be ignited, which is the main difficulty when using this response method.

In order to ignite the oil, the slick must be at least 1–2 mm thick to accommodate heat losses to the underlying water (Buist et al., 1999; Brzustowski and Twardus, 1982), in addition to other ignition requirements caused by, for example, the oil type weathering state (Fritt-Rasmussen et al., 2012). Since oil spreads out on open water to thicknesses well below 0.1 mm (Buist et al., 2013), mechanical or chemical measures are required to gather the oil and thereby increase the slick thickness.

Conventionally, fire-resistant booms have been used to collect and thicken spilled oil on open water (Buist et al., 1999; Potter et al., 2012). However, booms are less effective in ice-infested waters (Potter et al., 2012; Bronson et al., 2002) and are heavy and difficult to handle (Potter, 2010b). An alternative tool is a “herder”, a chemical surfactant that spreads out rapidly over a water surface. The primary characteristic of a herder is a high spreading pressure, making it energetically preferable for the herder instead of the oil to occupy the water-air interface (Garrett, 1969). When applied around an oil slick, the herder will ‘push’ the oil slick into a smaller surface area. As the surface area decreases, the slick thickness of the oil must increase. Herders have been shown to achieve post-herding thicknesses of 3–8 mm (Ross, 2007), which are sufficient for ignition.

Herders are of particular interest in water with a medium (3/10–7/10) ice coverage because fire booms have only been effectively used in ice coverages up to 3/10 (Potter, 2010a) and the ice inhibits the spreading of the oil above a 7/10 ice coverage (Brandvik et al., 2006; Ross et al., 1987). Experiments have shown that herders could effectively increase the slick thickness in this range of ice coverages (3/10–7/10) (Ross, 2007). Crude oil has also been successfully herded under swell wave conditions (Ross, 2012), on open sea (Buist et al., 2011) and in cold temperatures (−21 to 0 °C) (Ross, 2007) and herded oil slicks could reach burning efficiencies up to 94% of the oil (Ross, 2007; Buist et al., 2011). During the herding of oil in ice-infested waters, however, oil slicks were observed to break up into multiple slicks after the herder had been applied (Ross, 2007). This fracturing of the oil slick would inhibit flame spreading, since flames cannot spread between separate oil slicks.

There is currently very little knowledge on how the formation of multiple oil slicks would influence *in-situ* burning and the achieved burning efficiency, here defined as the wt% of oil removed from the water surface. Previous studies reporting the fracturing of herded oil slicks focused on the herded slick thickness and did not study the *in-situ* burning of these fractured slicks (Ross, 2007). Considering that one of the main uses of herders is to facilitate *in-situ* burning, the

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burning efficiency should not be reduced by fracturing of the oil slick during the herding process.

Fracturing of an oil slick may be due to the presence of ice on the water surface, since the formation of multiple slicks has not been observed in open waters under similar calm weather conditions (Ross, 2012). It is therefore important to map the effects of ice on the herding process in order to determine the ice conditions under which herders can effectively facilitate *in-situ* burning of oil. In this study the pre- and post-herding slick thickness, surface distribution and burning efficiency of a crude oil on ice-infested water were studied as a function of the ice coverage. Herding of oil in ice-infested water was studied in both small and intermediate scale experiments to investigate whether the results can be extrapolated to full scale scenarios.

2. Materials and methods

The experimental herder application procedure was designed to create semi-realistic testing conditions. Experiments were conducted in a small scale laboratory setup (1.0 $m^2 \times 0.5$ m (water depth) square water basin) and in an outdoor intermediate scale setup (19 $m^2 \times 1.0$ m (water depth) octagonal water basin) (Fig. 1). The water basins were filled with fresh water and artificially made brash ice (ice fragments <2 m in length (WMO, 2014)) was used to create ice coverages of 3/10, 5/10 and 7/10. The boundaries of the water basins should be considered as large ice floes, between which the oil could spread. DUC crude oil ($\rho = 0.85$ g/mL, $\eta = 6.75$ mPa·s), a light blend crude oil from the North Sea, was used in all experiments. The amount of oil used (200 g/m^2 of open water surface) was inversely proportional to the ice coverage in order to maintain the same open water surface area-to-oil ratio and achieve a similar spread thickness in each experiment. The herder used in this study, Siltech OP-40 (previously known as Silsurf A004-UP (Lane et al., 2012)), has been shown to sufficiently thicken crude oils in fresh and salt water for *in-situ* burning purposes (≥2 mm) (Ross, 2012). Because the herder performed better in salt water, the use of fresh water was considered to be the more conservative option.

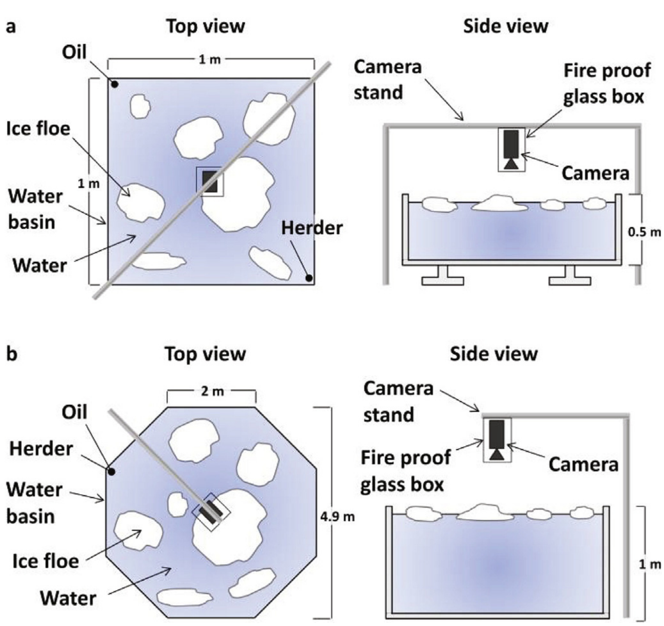

Fig. 1. Experimental setup for the small scale (a) and intermediate scale (b) experiments. Small scale experiments were conducted indoor and intermediate scale experiments were conducted outdoor. The "oil" and "herder" labels indicate the location in the basin where these products were applied on the water surface.

In a typical experiment, the DUC crude oil was poured slowly on the water surface from a corner of the basin and was allowed to spread for 30 min. The herder (Siltech OP-40) was then applied in a single corner of the basin, simulating the herding of oil at the edge of the spill towards its center (Fig. 2). After 30 min, the herded oil was ignited one slick at a time and allowed to burn until extinction. The burn residues were collected with 3 M hydrophobic absorption pads, were then dried overnight in an oven at 50 °C and weighed afterwards to determine the burning efficiency. A digital camera was used to monitor the experiment from above. Images were taken every 10 s to measure the surface area and surface distribution of the crude oil.

The experimental conditions of the small scale and intermediate scale experiments are summarized in Table 1 and their procedural details are described below. For the small scale experiments (indoors), the artificial brash ice was 3–5 cm thick and made from fresh water. The herder (50 μL/m^2 water) was applied in the corner opposite of the original spreading location of the oil (see Fig. 1a) and ignition of the oil slicks was attempted with a butane hand torch. The basin was thoroughly cleaned with a hot water solution of Alconox detergent powder (10 g/L), before and after each experiment, to remove the herder from the steel walls. Surface tension measurements of the water prior to applying the ice and oil were in the expected range (68–71 mN/m) and confirmed that the herder had been removed successfully. Each of the small scale experiments was conducted twice.

For the intermediate scale experiments (outdoors) the oil was applied in an upwind corner to ensure the oil would spread over the water surface. The wind had a significant influence on the spreading and herding behavior of the oil, which caused some repeatability issues and hence the experiments are shown individually in Table 1. Nevertheless, these issues were, after thorough analysis, not seen to alter the main outcome of the study. The recommended operational herder dose of 150 μL/(m^2 water surface) was used to overcome the effects of the wind (Buist et al., 2016). The herder was applied in the same upwind corner as the oil so that the wind would not inhibit the herding process (see Fig. 1b). Local wind speeds were measured on site using a wind speed meter (see Table 1). The brash ice in these experiments was made in $80 \times 50 \times 30$ cm^3 casts in a −20 °C freezer. Initial ice coverages of 3/10 were prepared, but due to melting of the ice during the preparation of the experiments with ice the actual ice coverages tested were 2/10 and 2.5/10. Ignition of the oil slicks was attempted with either a weed burner or a burner and 3–50 mL ignition gel (8:2:0.1 mixture of diesel, gasoline and G-760 gelling agent) that was poured and ignited on a central location of an oil slick. Surface tension measurements of the water (70–71 mN/m) prior to applying the ice and oil showed that there was no significant herder residue left in the basin in between experiments.

The ignition of a larger volume of free-floating herded oil (15 L) was also tested in the intermediate scale setup. During this experiment, the herder was applied in six doses of 473 μL of herder around the oil slick. After 30 min of herding, the oil slicks were adjacent to the basin boundaries and an additional 2100 μL was applied around the oil slicks to force the oil slicks onto the open water surface prior to ignition. The oil slicks were each ignited with approximately 50 mL of ignition gel and a weed burner.

The camera images were analyzed in Photoshop CC 2015 using color sensitive selection tools to select the pre- and post-herding oil slicks on the water surface. These tools were chosen over manual selection of the oil slicks to eliminate subjective bias. Pixel measurements of the oil slicks indicated the number of individual areas and were compared to the pixel area of the water basin to calculate the slick areas in m^2. Based on the initial oil volume (the weight of the oil divided by the density of the oil) and assuming a uniform thickness distribution, the average slick thickness of the oil could then be calculated (Ross, 2007).

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