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Importance of the slick thickness for effective *in-situ* burning of crude oil

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ABSTRACT

In order to improve the potential of *in-situ* burning (ISB), the importance of the oil slick thickness on two pure oils (*n*-octane and dodecane) and two fresh crude oils (Grane and REBCO) was studied in relation to the regression rate, boilover tendency, mass loss rate, burning efficiency and flame height. The experiments were performed in a new experimental apparatus, the Crude Oil Flammability Apparatus (COFA), which has been developed to study ISB of oil on water in a controlled laboratory environment with large water-to-oil ratios. The regression rate, average mass loss rate and burning efficiency reached a constant maximum value for all oils at slick thicknesses exceeding 10–20 mm. For thinner initial slick thicknesses, these values were greatly reduced, most likely due to heat losses to the water. A further increase in the initial slick thickness could not improve the burning efficiency above 75% for the crude oils, showing that it only has a limited effect on the burning efficiency as higher burning efficiencies have been reported for larger scales. Furthermore, the results showed that the burning mechanisms differ for pure and crude oil, indicating that the hydrocarbon mixture in crude oils changes as the burning progresses. This observation merits further research.

1. Introduction

The burning of crude oils is of great interest as a response method to oil spills, a method known as *in-situ* burning (ISB) [1–5]. In practice, this response method commonly features the collection of accidently spilled oil on a water surface in a so-called “fire boom”, followed by the ignition of the oil slick [1,6] and thereby removing the oil from the water surface. Particularly for potential oil spills in the ice-infested waters of the Arctic, this response method has gained increased attention (see for example Sørstrøm et al. [7], AMAP [8], Nuka Research & Planning Group [9] and Buist et al. [10]). Due to the relatively minimal logistics of ISB, relatively low costs [11] and its applicability at most levels of ice coverage compared to the more conventional mechanical clean-up methods [9,12], ISB has a good potential of cleaning up oil spills in the Arctic.

One of the main challenges of ISB is achieving a high burning efficiency (BE), which in this study is defined as the amount of oil (in percentages of the original spill size) removed from the surface of the water during the burning process. While high BEs of up to 99% have been achieved in both laboratory and large scale field experiments [13–17], lower BEs as low as 40% have also been reported [18–20]. As these experiments have been performed under widely varying conditions, such as differences in temperatures, oil types, oil amounts and the weathering state of the oils, it is difficult to determine which factors are responsible for these BE variations. In order to gain a better understanding of the factors that influence the BE and what their effects on the burning process are, it is of interest to perform a parametric study of these relevant factors. A more detailed understanding of the burning process and related environmental effects should allow for better informed decisions on whether or not ISB is a favorable response method in case of an (Arctic) oil spill.

Oil spills can be found in a variety of appearances depending on the environment, and the slick thickness can vary greatly from one spill to another. On open sea, oil slicks spread out freely and become as thin as <1 μm, also known as oil sheens. In ice-infested water such as in the Arctic, the ice can inhibit the spreading of the oil, allowing it to accumulate to create a thick slick of up to 10–40 mm [10]. During an ISB operation, the slick thickness can be influenced through the towing speed of the fire boom and the area

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Abbreviations: BE, burning efficiency; COFA, crude oil flammability apparatus; ISB, *In-situ* burning; PGC, pyrex glass cylinder; WMLR, water mass loss rate

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it encloses (i.e. the distance between the ships) [1]. The oil slick thickness upon ignition is a very important parameter of ISB as it affects many aspects of the burning process. While it is generally accepted that a minimum slick thickness of about 1–3 mm is required to ignite the oil and to acquire a self-sustaining fire (due to heat loss to the underlying water surface [10]), the importance of a variation in the slick thickness has not been studied in detail. The initial slick thickness has been reported to be the “key parameter” that influences the BE [10]. A thicker slick should lead to an easier ignition and higher BE [10] and thicker slicks might therefore be preferred for ISB.

However, a precise relation between the BE and initial slick thickness is unknown as of yet. Thicker slicks also result in more violent and longer boilovers and can lead to (relatively) more residue formation [10, 21–23]. While boilovers have not been observed during burnings featuring towed fire booms or in waters with currents [10], it is still relevant to take into account for the safety aspects of ISB. The precise physical and chemical mechanisms of boilovers are still largely unknown and hence it is still a somewhat unpredictable phenomenon. More residue formation will require a more extensive cleanup after the burning, which would complicate the logistics. Furthermore, due to the spreading of oil on sea, it is often more complicated to gather a certain volume of oil as a thick slick than a thin slick for burning operations. Thus, it is relevant to find an optimal slick thickness that maximizes the beneficial effects on the ignition time and burning efficiency, while minimizing the logistics and safety issues. Therefore, the effects of the initial oil slick thickness on the regression rate, boilover tendency, burning efficiency, flame height and mass loss rate were studied herein to determine the importance of the initial slick thickness for ISB operations.

2. Materials and methods

The oil-on-water burning experiments were performed in a newly developed experimental setup, the Crude Oil Flammability Apparatus (COFA), shown in Fig. 1 (for more images see Brogaard et al. [24]). The apparatus was developed to represent realistic conditions such that extracted parameters can be transferred directly to field studies. To achieve this, the COFA was designed amongst others to have a large body of water to create an oil–water interface comparable to large scale. These design choices were made to mitigate the complications with heat transfer issues that could be seen in studies with less or no surrounding water [3,23,25,26]. While heat transfer models have been used to accommodate for oil–water interface interactions (e.g. [27,28]), the uncertainties remained significant. The COFA setup was verified against large scale field experiment data from Brandvik et al. [15].

For measuring the regression rate, boilover tendency, burning efficiency and flame height the regular COFA setup was used. The Pyrex Glass Cylinder (PGC), with a height of 340 mm and diameter of 160 mm, was placed in the middle of a stainless steel water bath of $1.0 \times 1.0 \times 0.50\ \mathrm{m}^3$ ($L \times W \times H$) that was placed under an exhaust system. A stainless steel foot for the PGC was used to ensure free water flow underneath, which is important for minimizing the difference in the ullage height throughout the experiment. The bath was filled with water (approximately 390 liters of fresh water of 5–25 °C) until it reached about 1–5 cm from the top of the PGC. For the mass loss rate, the COFA setup was adjusted to allow for the use of a scale. The PGC was placed on an open foot in a metal bucket of $0.3 \times 0.3 \times 0.4\ \mathrm{m}^3$ ($L \times W \times H$) filled with fresh water of 5–25 °C, which stood on a scale that was covered by an aluminum plate ($0.9 \times 0.9\ \mathrm{m}^2$) to protect it from liquids ejecting during

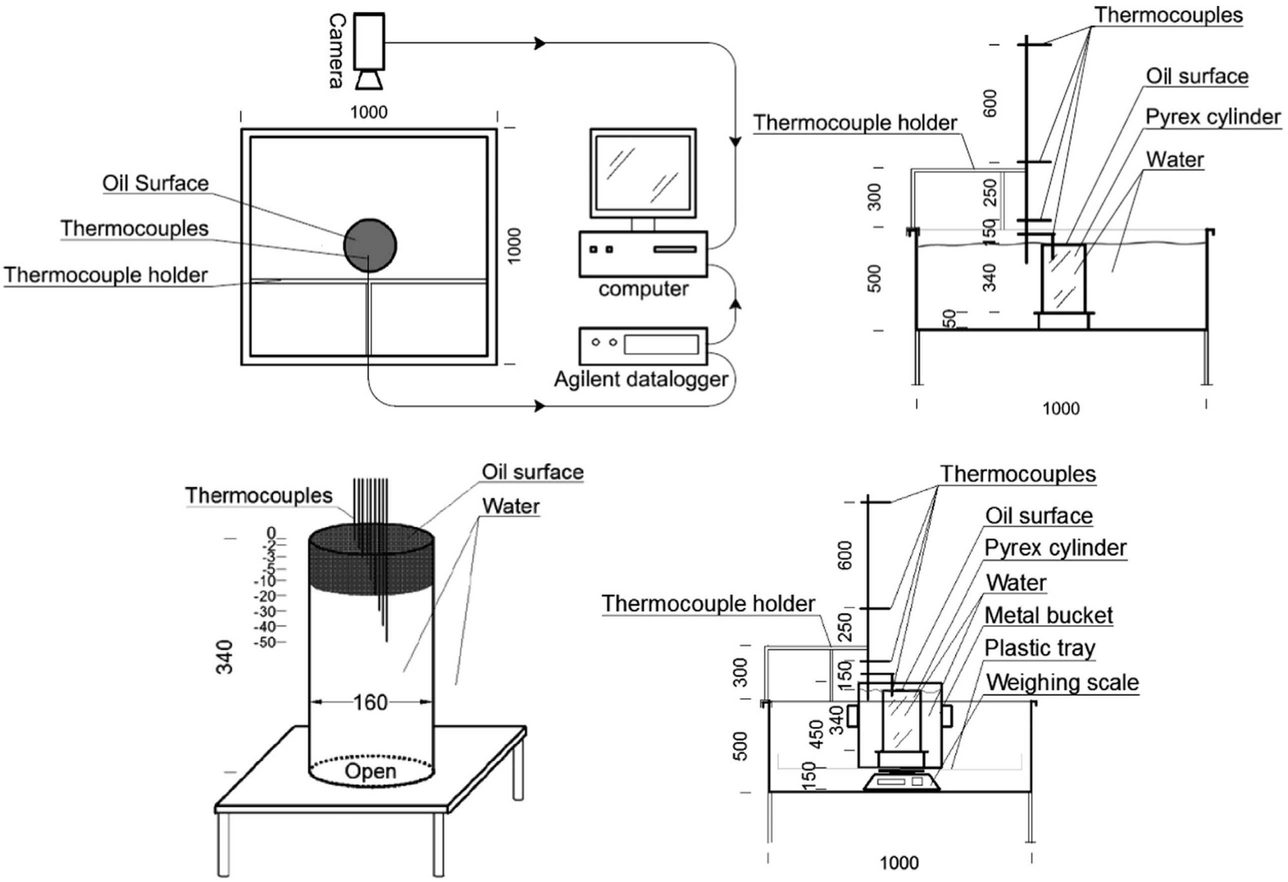

Fig. 1. Conceptual outlines of the COFA setup from a top view (top left) and cross sectional view (top right), the PGC on its open steel foot showing the thermocouple distribution and oil layer (bottom left) and the mass loss rate setup in the COFA (bottom right). All numbers are in mm. Adapted from Brogaard et al. [24].