In-Situ Burning of Crude Oil on Water: A study on the fire dynamics and fire chemistry in an Arctic context

The fire dynamics and fire chemistry of in-situ burning of crude oil on water was studied in order to improve predictions on the suitability of this oil spill response method. For this purpose, several operational parameters were studied to determine the factors that control the burning efficiency of in-situ burning, i.e. the amount of oil (in wt%) removed from the water surface by the burning process. The burning efficiency is the main parameter for expressing the oil removal effectiveness of in-situ burning as response method and is thus relevant for suitability predictions of in-situ burning as oil spill response method. The parameters studied were the initial slick thickness of the oil, the vaporization order of burning crude oil, the ignition of fresh and weathered crude oils on water, the influence of the burning area, the effect of the water layer below the burning oil and the use of chemical herders in ice-infested water to thicken spread oil slicks.

All the experimental work, except for the crude oil herding studies in ice-infested water, was conducted in several small and intermediate scale setups with oil pool diameters between 0.1 m and 1.1 m. The main apparatus used in this study featured a water basin (water volume of 1.0 x 1.0 x 0.50 m³) in which a 0.34 m high Pyrex glass cylinder with a diameter of 0.16 m was placed to contain the oil samples. Several fresh crude oils, refined oils, and pure oils, which were used as reference fuels, were burned in this setup to study the surface temperature, burning rate, flame height, burning efficiency and chemical composition of the burn residue as a function of the oil type, the initial slick thickness and other experimental conditions.

The results showed that crude oils burned distinctively different from pure oils and refined fuel oils, as no steady state burning behavior was observed for the crude oils. Whereas the pure reference oils burned with relatively constant surface temperatures, burning rates and flame heights, the surface temperature increased and the burning rate and flame height decreased over time for the crude oils. Through a comparison with predictions of these parameters from vaporization order models for multicomponent fuels, it was shown that the components in a crude oil vaporize in the order of decreasing volatility. This volatility controlled vaporization order was confirmed by a principal component analysis of the chemical composition of the residues as a function of the burning efficiency. The differences in chemical composition between the 85 m/z ion chromatographs, which include the n-alkanes (C9-C31), clearly showed that the abundance of light components decreased with increasing burning efficiency.

A mathematical analysis of the heat transfer mechanics of oil pool fires on water showed that the net heat feedback to the fuel surface depends on the pool diameter due to the heat losses to the water layer. Due to the fact that burning crude oils follow a volatility controlled vaporization order, these heat losses furthermore increase as a function of the burning time. By supporting this mathematical analysis with experimental results, it was shown that the burning area is the most important parameter of the burning efficiency for crude oil burning on water, with larger pool areas leading to higher burning efficiencies. This size dependency of the burning efficiency was attributed to the increased heat feedback to the fuel surface for large scale pool fires, as compared with small scale fires, that could cancel out the heat losses to the water. Small scale burning experiments subjected to an incident heat flux from a conical heater confirmed that an increased incident heat flux increased the burning efficiency of both fresh and weathered crude oils. At incident heat fluxes representative of large scale fires (diameter ≥ 2 m), however, the burning efficiency did not reach the high efficiencies (≥ 90%) reported for large scale in-situ burning operations. It was therefore deduced that the high burning efficiencies observed in large scale crude oil fires on water are not only caused by an increased heat feedback, but by other factors inherent to large scale fires as well.

Further studies on the fire dynamics of large scale crude oil fires on water should be conducted to identify the factors associated with a large pool diameter that are responsible for the high burning efficiencies. The initial slick thickness was primarily of importance to the ignition of oil slicks in the small scale experiments. Once a minimum ignitable thickness that accommodated for the heat losses to the water layer was reached, the results suggested that further increasing the slick thickness has little influence on the burning behavior of crude oil on water. The thickening of simulated crude oil spills in ice-infested water with a chemical herder, a surfactant that rapidly spreads over a water surface, also indicated that the slick thickness is only a minimum requirement for ignition. Crude oil spread on water with 2/10-7/10 ice coverages in small (1 m² water surface) and intermediate (19 m² water surface) scale experiments was successfully thickened from non-ignitable oil spill thicknesses of 0.1-2 mm to ignitable herded thicknesses of 3-7 mm.

During the herding process, however, the crude oil slicks were observed to fracture as a function of the ice coverage. This fracturing process complicated and inhibited ignition of small slicks, even though the herded oil slicks theoretically had an ignitable slick thickness. The resulting burning efficiencies were therefore lower than expected based on the burning areas. Herders thus successfully facilitated in-situ burning of oil in ice-infested waters, but ignitability issues of fractured oil slicks should be addressed to improve burning efficiencies of herded oil slicks.

Ignition studies of fresh and weathered crude oils and a fresh heavy refined oil under a conical heater showed that the critical heat flux for weathered oils and heavy oils with little volatile components was 5-10 kW/m². At higher incident heat fluxes (≥ 20 kW/m²), ignition was very rapid for fresh and weathered oils and the weathering state (evaporated or emulsified) did not significantly affect the ignition or burning efficiency. These results correspond well with the reported need for large ignition sources to ignite and spread flames on weathered oils on water. Once ignited, however, the weathering state is not expected to influence the burning efficiency for large scale fires, which is in accordance with the postulated theory on the size dependency of the burning efficiency.

The boiling phenomenon, i.e. the explosive burning of crude oil, was shown to be a function both of the superheating of water and the chemical composition of the burning oil. Cooling of the water layer below the burning oil, by introducing a current in the water body, prevented boilover from occurring for oil burned in the small scale water basin. Boilovers were also observed during the burning of a heavy crude oil with a substantial light fraction without a water layer, however, which suggests that water is not essential for boilover occurrence. Further studies are required to determine the conditions under which these boilovers without a water layer can occur.

Overall, the results showed that the studied operational parameters, apart from the pool diameter, only have a limited
effect on the efficiency of in-situ burning as oil spill response method. This strongly suggests that high burning efficiencies are inherent to operational scale crude oil fires on water. Operational and environmental conditions such as the weathering state of the oil and the initial slick thickness only influence the ignitability of the oil. Once ignition and flame spread on a large oil slick are successful, high burning efficiencies are expected simply due to the scale of the fire. As such, the main parameter that determines the suitability of in-situ burning as oil spill response method becomes the ignitability of the oil. This ignitability parameter is depending on complex fire dynamics aspects, but can be expressed in terms of the heat flux that the ignition source needs to be able to provide to the oil surface to ignite the oil. From an operational point of view, predicting the suitability of in-situ burning can thus be reduced to answering the question whether the strength of the required ignition source to ignite the spilled oil is practically feasible.

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