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Ignitability of crude oil and its oil-in-water products at arctic temperature

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ABSTRACT

A novel platform and procedure were developed to characterize the ignitability of Alaska North Slope (ANS) crude oil and its water-in-oil products with water content up to 60% at low temperatures (-20 – 0 °C). Time to ignition, critical heat flux, in-depth temperature profiles were investigated. It was observed that a cold boundary and consequent low oil temperature increased the thermal inertia of the oil/mixture and consequently the time to sustained ignition also increased. As the water content in the ANS water-in-oil mixture increased, the critical heat flux for ignition was found to increase. This is mainly because of an increase in the thermal conductivity of the mixture with the addition of saltwater. The results of the study can be used towards design of ignition strategies and technologies for *in situ* burning of oil spills in cold climates such as the Arctic.

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1. Introduction

When oil spills occur in the arctic they present a unique challenge for remediation due to the remoteness of the location, extremely cold temperatures, and the presence of ice amongst the spilled oil. Each of these challenges delay initial response and slow the time to successful intervention with heavy machinery for mechanical recovery [1]. In these circumstances, *In Situ* Burning (ISB) defined as igniting and burning the spilled oil in place has been shown to be an effective means for cleanup [2]. Several factors, however, greatly affect the degree of success of ISB such as weathering, level of emulsification, and the presence of a cold substrate in the form of seawater, and sea ice. Previous studies have examined the effects of weathering and emulsification, usually in combination, on the ignition characteristics of crude oil and have explored igniters to initiate ISB. However, these studies have been conducted at ambient temperatures above that of the arctic [3–6]. The objective of this study is to systematically analyze emulsification and influence of a cold boundary on the ignition behavior of an oil slick. A series of experiments were conducted using an experimental platform and procedure developed to determine material properties for characterization of the ignition of ANS crude oil in arctic condition. The experimental data was then used to clarify the ignition characteristics of different ANS crude water-in-oil products comparatively.

2. Experimental apparatus and procedure

Experiments were performed using a specially engineered vessel whose walls were cooled and maintained at sub-zero temperatures to simulate arctic boundary conditions on a layer of ANS crude oil and its water-in-oil products. The burning properties of ANS crude are discussed in Farahani et al. [7] and Shi et al. [8]. In-depth temperature profiles, time to ignition, and applied external heat flux data were measured to determine ignition probability for ANS crude oil at various low temperatures and levels of emulsification (water content).

2.1. Apparatus

Fig. 1 shows a sketch of the experimental apparatus. An external refrigerated circulating bath (PolyScience Performance Digital 15 L Recirculating Bath model EW-12210-26) was used to circulate coolant (Dynalene HC-50) to a copper coil cooling jacket around a 10 cm diameter and 5 cm deep thin-walled (1 mm) stainless steel vessel. Both the walls and the bottom of the vessel were cooled to a preset temperature to simulate an oil layer bounded by the arctic sea ice. The temperature of the coolant fluid was set and monitored by the circulating bath ensuring a constant temperature boundary condition at the walls and bottom of the ignition vessel. External heat flux was applied to the oil surface by a radiant heater [9] at a distance of 8.9 cm. The heat flux from the heater to the oil layer was uniform and could be varied in steps of 0.1 kW/m^2 increments by adjusting the current to the heater. The current to heat flux calibration was achieved using a water cooled heat flux gauge (Medtherm). A spark ignitor was placed 1.3 cm above the oil surface offset from the centerline by 1 cm. During testing the spark ignitor was cycled for 10 s of active spark followed by a 10 s off cycle. This procedure

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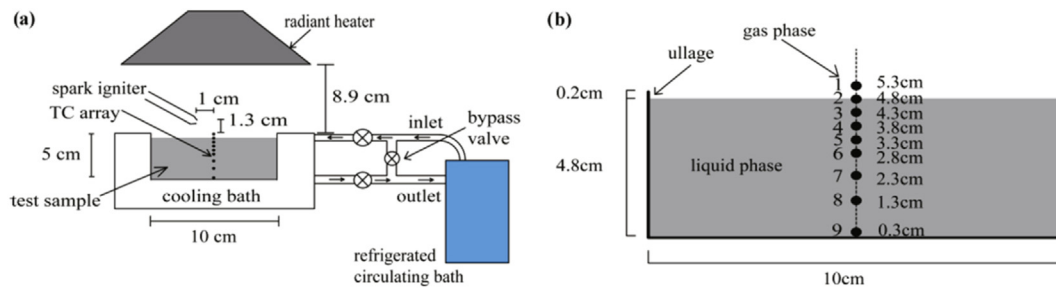


Fig. 1. a) Experimental setup. b) Cross section of ignition vessel indicating location of oil layer and thermocouples.

prevented localized heating from a constant spark. A thermocouple array was placed along the centerline of the oil layer at heights (from the bottom) of 0.3 cm, 1.3 cm, 2.3 cm, 2.8 cm, 3.3 cm, 3.8 cm, 4.3 cm, 4.8 cm, and 5.3 cm. An additional thermocouple was placed on the vessel wall to monitor the surrounding temperature of the oil layer. The thickness of the oil layer was maintained at 4.8 cm for all experiments. The small ullage of 2 mm allowed for slight oil expansion that was observed in some experimental trials. The central thermocouple array thus provided in-depth temperature profile in the oil layer and also the gas phase, which was 5 mm above the oil surface.

A total of 84 experiments were conducted at oil temperatures of 0, -10 , and -20 °C for water-in-oil mixtures with water content of 0% (pure ANS crude), 20%, 40%, and 60%. The applied heat flux for each combination of oil temperature and water-in-oil mixture level was varied to determine critical heat flux, which is the minimum energy required to sufficiently heat the oil and provide enough fuel vapor for ignition and sustained burning. Sustained ignition is defined as flaming combustion across the oil surface for four seconds or more after the spark igniter is removed [9]. Once the critical heat flux was determined, three additional experimental sets were conducted at heat flux increments above the critical heat flux. Each set of oil temperature, water-in-oil mixture, and applied heat flux was tested in triplicate with a total of twelve experiments for each combination of emulsification level and temperature.

2.2. Test sample preparation

Oil samples were pre-conditioned in sealed 800 mL vessels in a recirculating bath set at the required temperature for 24 h to ensure uniform temperature throughout the sample. Water-in-oil mixtures were created using artificial saltwater (3.5% salinity) and fresh ANS crude, and prepared using a closed-loop mixing system until a stable water-in-oil mixture was achieved, as indicated by no separation after 48 h. The system was closed to ensure the negligible weathering during water-in-oil mixture preparation. Most crude oils and petroleum products require weathering (evaporation) to form stable water-in-oil products [10,11]. Studies show that at warm temperatures (~ 15 °C) ANS crude must evaporate to lose more than 15% of volume to form stable water-in-oil products, but at freezing temperatures even fresh ANS crude forms stable water-in-oil products [0]. In the current study both temperatures of the sample and the testing environment were below the freezing temperature (0 to -20 °C), and water-in-oil mixtures formed in the study were deemed stable.

Several factors contributed to the difficulty encountered during testing at arctic temperatures. The test sample needed to be poured into the vessel located under the conical radiant heater. However, the viscosity of the oil sample increased severely with the decreasing sample temperature and increasing level of water content. When the sample temperature dropped to and below -10 °C, the water-in-oil mixtures with water content larger than 20% became highly viscous and had to be scooped into the ignition vessel from the conditioning containers. Therefore, it was difficult to achieve a uniform surface, leading to higher uncertainty in the time to ignition.

3. Results and analysis

Fig. 2 shows the time to ignition as a function of the external heat flux for pure ANS crude oil and water-in-oil mixtures of 20% and 60% maintained at -10 °C. Each data point is an average of three experimental trials, with variation shown in the form of error bars. It shows that as the heat flux decreased, the time to ignition increased, up to a point where no ignition was possible. This threshold heat flux between ignition and no ignition is defined as the critical heat flux [13] and indicated by the vertical dotted lines in Fig. 2. Pure ANS crude oil shown to be otherwise ignitable at ambient temperatures [5,6,14] required a critical heat flux of 1.87 kW/m² for sustained ignition at low temperature of -10 °C. The main reason for this difference was the cold sidewall, which created significant thermocapillary convective effects. The boundary condition thus reduced the flammability of pure ANS. As the ANS crude was emulsified with water, the critical heat flux required for sustained ignition increased significantly up to 4.06 kW/m² for 20% water content and 10.55 kW/m² for 60% water content. The water content affected the ignition process by increasing the effective thermal capacity of the oil sample (including latent heat requirement). Further, the released water vapor would dilute the oil vapor effectively increasing the gas-phase induction time. Thus, critical heat fluxes were found to increase with increasing moisture content [15–17]. Secondly, addition of water increased the thermal diffusivity of crude oil, mainly because of the higher conductivity of water compared to ANS crude oil [18]. This caused an increase in heat loss in-depth with increasing water content also leading to an increase in the critical heat flux with increasing emulsification levels as shown in Fig. 2. These primary controlling parameters are further analyzed using in-depth temperature profiles.

3.1. In depth temperature profile

In-depth temperature profiles obtained with critical heat flux application for pure ANS crude oil and 20% water-in-oil mixture both at -20 °C at the time to 50% temperature at ignition (T_{ig}), time to ignition (t_{ig}), and local temperature maxima immediately following ignition are shown in Fig. 3, which shows the in-depth heat transfer during the ignition process. Note that the wall temperature (not shown) was constant during the entire process as the circulating coolant bath maintained the temperature at a fixed pre-determined value of -20 °C in this case. Firstly, for pure ANS (Fig. 3a) the thermal wave did not penetrate to the bottom of the vessel showing that the oil layer behaved as thermally thick during the ignition process. Further, the thermal penetration depth (δ) for pure ANS is about 1.3 cm showing that oil layers with thicknesses of 1.5 to 2 cm trapped in ice in the arctic environment will behave as thermally thick. The penetration depth however increased to about 3.0 cm for the case with 20% water content maintained at -20 °C (Fig. 3b). This difference is mainly because of an increase in the thermal conductivity of the water-in-oil mixture as discussed by Wu et al. [6]. It's also possible that the saline water used in the study increased the mixture conductivity because of the presence of salt [19], as the thermal conductivity of saline water/ice increases with a decreasing temperature [19]. This may lead to significant in-depth conduction heat

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