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Effect of operational parameters on the recovery rate of an oleophilic drum skimmer

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Abstract

The primary objective of this research was to determine the relationship between operational variables and oil spill recovery rates, by performing a full-scale oil spill recovery test using an oleophilic drum skimmer. Prototype interchangeable oleophilic skimmer drums with aluminum, polyethylene and Neoprene surfaces were fabricated and tested at the field scale at the Ohmsett-National Oil Spill Response Test Facility. This study determined the effect of the recovery surface material, oil properties, oil slick thickness, temperature and drum rotational speed on the oleophilic drum skimmer recovery rates. It was found that the selection of the recovery surface material can increase the recovery rates up to 20%. The increase in oil slick thickness from 10 to 25 mm led to up to two times higher recovery rates for a viscous oil, but did not have any noticeable effect on the recovery rates of light oil.

Keywords: Oil spill; Response; Recovery; Skimmer; Efficiency; Recovery surface

1. Introduction

Mechanical recovery is the most commonly used oil spill response technique [1]. This technique physically removes oil from the water surface, even in the presence of ice [2]. Unlike other cleanup techniques, mechanical recovery can be efficiently applied to treat emulsified oils as well as oils of variable viscosities (6–20,000 mPa s). A weakness of mechanical cleanup is the recovery rate. It may be very time consuming and expensive when employed on a large scale, and require a large amount of personnel and equipment, and every additional hour of cleanup time can significantly increase the cost of recovery. A more efficient recovery device can thus reduce the cost significantly and reduce the risk of oil reaching the shoreline.

The adhesion (oleophilic) skimmer is one of the most common types of mechanical recovery equipment. It is based on the adhesion of oil to a rotating skimmer surface. The rotating surface lifts the oil out of the water to an oil removal device (e.g., scraper, roller, etc.). A number of studies have been undertaken to test the recovery rate of various skimmers [3–11]. The goal of these studies was to compare the recovery rates of various skimmers, but they did not perform a systematic analysis of the effect of operational parameters such as spill thickness, temperature, drum rotational speed, etc., on oil recovery rates. The skimmers tested in these studies had different configurations, dimensions, capacities and recovery modes. In most cases several operational parameters were changed simultaneously during each test making it difficult to distinguish the effect of each variable separately. The current study specifically evaluated both design and operational parameters independently, providing key information about the influence of these parameters on the overall oil recovery rate.

Prior to this study, the interfacial tension between different materials that could be used in the recovery surface of the skimmer and various oils was evaluated [12]. Although interfacial tension is a very important factor in the initial adhesion of oil to the recovery surface, the wetting sequence is important. Under typical conditions, the skimmer's drum rotates first into the oil, and then lifts the oil towards the scraper. Interfacial tension plays an important role in wetting the recovery surface in the first rotation. However, oil viscosity and cohesion become more important as the oil is transported up to the scraper, since they control the thickness of the oil on the recovery surface and

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significantly influence overall recovery rates. Since the scraper does not remove 100% of the oil from the drum, a thin oil film is present in subsequent rotations. The ability of oil to form and maintain a thicker film on the surface and the ability of the material to retain oil becomes more important.

2. Methods

2.1. General

Ohmsett (Oil and Hazardous Materials Simulated Test Tank) is the world's largest tow/wave tank designed to evaluate the performance of equipment that detects, monitors, and cleans up oil spills under environmentally safe conditions. Ohmsett is located on the waterfront of the Naval Weapons Station Earle, in New Jersey. The facility is maintained and operated by the U.S. Department of the Interior, Minerals Management Service (MMS) and is open year-round for use by industry, academia, and federal agencies (US and foreign) to conduct full-scale oil spill research and development programs.

A number of drums were manufactured and retrofitted to an existing skimmer at Ohmsett. The skimmer was used to recover an oil slick in a controlled environment. The effect of each design or operational variable on oil recovery rates was evaluated.

The major test variables were:

- Oil type (Diesel, Endicott, and HydroCal 300).
- Oil slick thickness (10, 25 and 50 mm).
- Drum rotational speed (30, 40, and 65 rpm).
- Ambient temperature (10–15 °C and 25–30 °C).
- Drum surface material.

2.2. Materials

Three materials (aluminum, polyethylene, and Neoprene) were used. The width of the drums was 25.4 cm; the diameter of the drums was 35.6 cm. To eliminate the variables that could be introduced by using different skimming systems, a frame-type drum skimmer (Elastec Minimax) was used for all tests. This skimmer type uses a simple smooth drum constructed of an oleophilic material that is rotated through the oil layer. The adhering oil is subsequently removed by a plastic blade (scraper) to an on-board recovery sump. The advantage of this configuration is that drums of different candidate materials are relatively easy and inexpensive to manufacture. The drums were manufactured to the same physical specifications so that they could be interchanged in the skimmer frame. The drums are durable, easy to handle, and easily changed during a set of tests.

2.3. Test oils

To select the most efficient oil spill response method, it is important to first understand oil chemistry as well as the physical processes associated with oil adhesion to the recovery surface. Oil is a complicated mixture of many components, and its behavior largely depends on its initial properties as well as the environmental conditions at the spill site. Oil spill recovery is complicated by the fact that the physical properties of the oil and its composition vary over a wide range, from very light fluids with low viscosity to very viscous oils with high asphaltene and wax content that may become semi-solid when spilled in a cold environment. The adhesion between spilled oil and the recovery surface depends on the oil composition and properties at the time of recovery. These characteristics change over time as the oil weathers.

Diesel, Endicott (an Alaskan crude oil), and HydroCal 300 (a lubricant oil) were used in the tests to study the effect of oil properties on the recovery rates. These oils have significantly different properties (Table 1), which allowed us to test the recovery surfaces on a range of possible recovery conditions. Diesel was only tested during the second test, at colder temperatures, since it was added later to the protocol.

2.4. Test protocol

The tests at Ohmsett were carried out in two test series. The first series was conducted in August of 2005 at an average ambient temperature of about 25–30 °C. The second series was completed in October of 2005 at an average ambient temperature of about 10–15 °C. Diesel was only tested in the second series, since it was not originally part of the protocol. The objective was to simulate oil spills under variable environmental conditions, and to determine the effect of temperature and oil viscosity on overall oil spill recovery rates. Future tests are planned at freezing conditions. The experimental setup is presented in Fig. 1.

The following test protocol was used in this study:

(a) A test drum was installed into an Elastec MiniMax skimmer frame. Although this skimmer has two drums, for these tests only one of them had scraper and was used to collect oil. The recovery rates estimated during the test correspond to one dram only. The skimmer assembly was secured in the center of the test tank, which was filled with seawater.

Table 1
Properties of oils used in Ohmsett field tests

Oil type	Density (kg/m^3)		Viscosity (mPa s)		Surface tension (mPa s)		Asphaltenes (%)
	15 °C	25 °C	15 °C	25 °C	15 °C	25 °C	
Diesel	833	823	6	2	27.5	27.1	0
Endicott	923	907	92	50	31	28.7	4
HydroCal 300	921	905	340	162	32.5	31.8	0

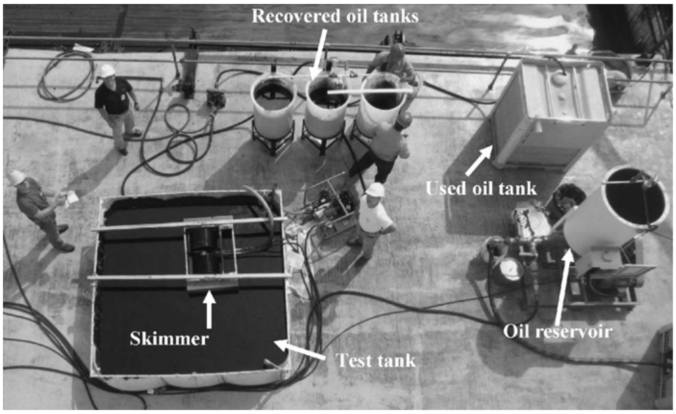

Fig. 1. Test setup at Ohmsett.

(b) A known volume of test oil was added to the test tank. This established an oil slick of known thickness. Slick thickness was controlled to a predetermined level throughout a given test. As the oil skimmer recovered oil from the test tank, additional oil was pumped from the oil reservoir at approximately the same rate. In this way, the slick thickness was controlled to within ±20%. After a given test ran, an accounting of oil volume recovered and oil volume distributed provided data for a mass balance. Throughout the runs, the oil film thickness was measured using two methods. An approximate thickness was estimated through the volume of oil in the known area. Although capillary forces formed a meniscus at the point of contact of the oil with the walls, the amount of oil collected in the meniscus was negligible compared to the total volume of oil. In addition, oil thickness was monitored through a transparent cylinder (approx. 20 cm long), one end hermetically sealed and the other end open to the atmosphere. The cylinder was held vertically within the oil slick and was dipped well below the oil/water interface. Thickness measurements were taken from inside the cylinder. The measured thickness was within 20% of the estimated thickness.

(c) The dram rotational speed was controlled with the hydraulic system provided with the Elastec MiniMax system. Varying the speed of the hydraulically driven skimmer drum controlled the encounter rate of the oleophilic surface with the oil front. A strobe and target marker on the drum helped to ensure proper control of rotational speeds. Three rotational speeds (30, 40, and 65 rpm) were used for most of the tests.The first two speeds represented the regular operational conditions of a drum skimmer, with minimal free water skimming. The 65 rpm speed represented the maximum rotational speed that could typically be achieved by this particular skimmer. At this speed, more oil was collected, but more free water was entrained by the drums, particularly for thinner oil slicks (10 mm). A higher rotational speed also emulsified the oil to a greater extent.

(d) At the beginning of each test, a preliminary phase took place. This involved recovering oil while adjusting the operating parameters, achieving a steady state, and establishing reliable data collection. During this preliminary phase recovered oil was returned to the test tank.

(e) Once steady state had been established, recovered oil was diverted to a recovery vessel, and the recovery period was timed. Tests with Endicott and HydroCal at 25 mm oil slick thickness were conducted for 5 min during the first test series. These tests indicated that 3 min of test were sufficient to collect all necessary information. All other runs during the first test series and all runs during the second test series were conducted for 3 min.

(f) At the end of each test run, the total amount of fluids (oil and water) was measured. Water was then taken out from the bottom of the collection tank for several minutes until no more free water was evident, and the remaining product was measured again. A sample of the oil or oil emulsion was taken to measure the water content via coulometric Karl Fischer titration. By subtracting the amount of free and emulsified water from the volume of total recovered product, the net amount of recovered oil was determined. Recovery rate was determined by dividing net recovered oil by the duration of recovery test.

(g) The initial oil and water temperature, oil and water surface temperatures during the test, and ambient weather conditions were documented.

3. Results

Oil recovery rate was defined in terms of the net amount of oil recovered per unit time (in liters per minute). The amount of recovered oil was estimated by subtracting the volumes of free and emulsified water from the volume of the total recovered product. The estimated experimental error in determining the recovery rate is ±0.5 l/min or less for all experimental runs. Fig. 2 shows the recovery rate and composition of fluid (oil and water) using various drams at 40 rpm.

In most cases, net oil recovery rates for HydroCal were higher than the ones for Endicott oil. This is due to the fact that the higher viscosity of HydroCal allows for a formation of a thicker oil film on the dram surface. Therefore a higher amount of oil is recovered per dram rotation. Diesel had the lowest recovery rates among these oils due to its low viscosity.

Oil recovery is also a strong function of oil spill thickness under most conditions. For HydroCal there was significant benefit from increasing the oil slick thickness from 10 to 25 mm, both in terms of total recovery (oil and water) as well as net oil recovery, under all conditions. Based on some limited testing (HydroCal at 25–30 °C), it appears that booming the oil spill to achieve an oil slick thickness greater than 25 mm results in a decrease in recovery rate, which was unexpected.

There is up to 20% difference in the recovery rates of various dram materials. Aluminum dram had the lowest recovery rates in most cases. The elastomeric material (Neoprene) was most efficient recovering HydroCal at 25 °C and diesel, although under other conditions polyethylene performed better. For Endicott, polyethylene recovered more oil at the lower temperatures, while at the higher temperatures there was little difference between the three materials.

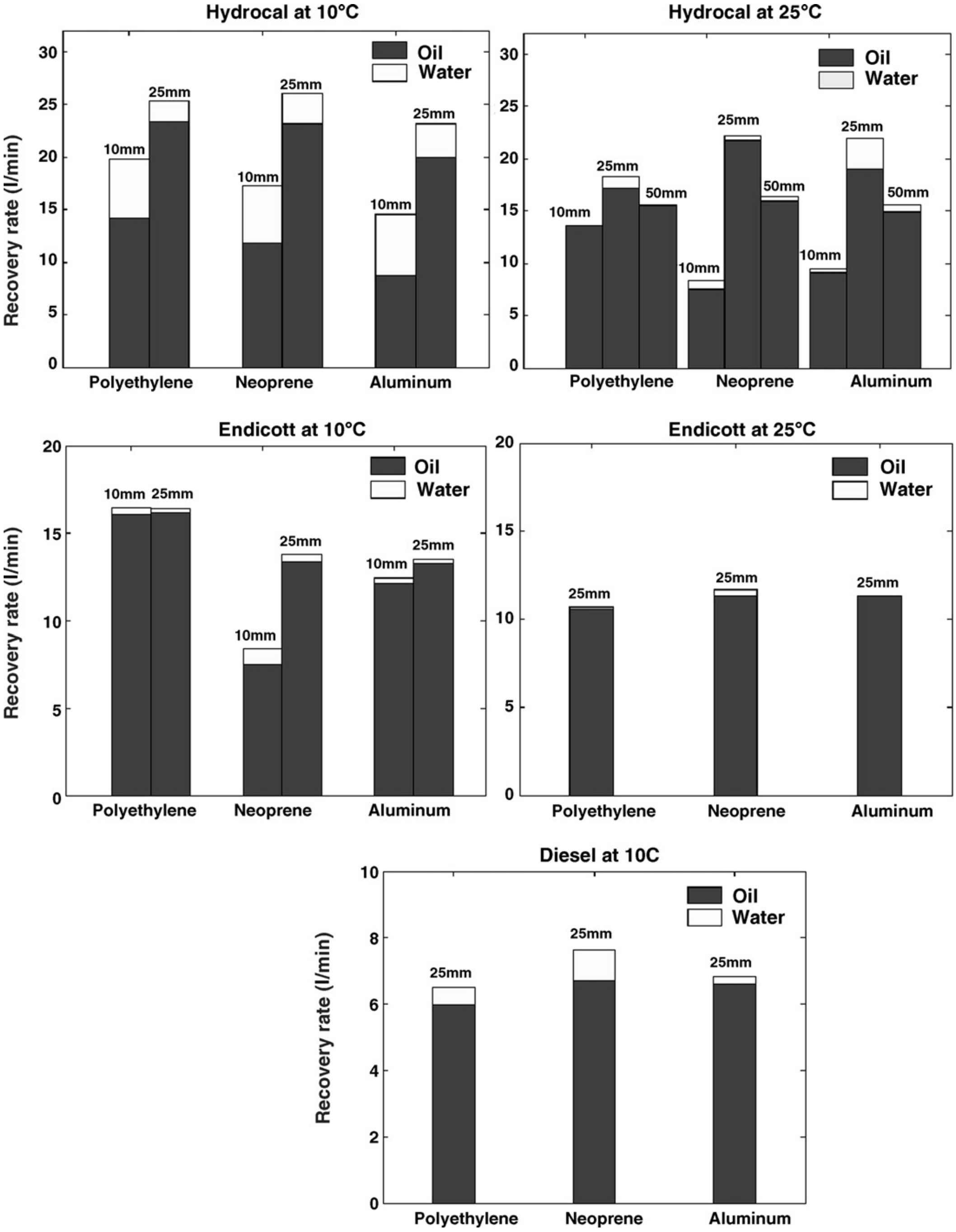

Fig. 2. Product recovery (oil and water) by various drums at 40 rpm. Oil slick thickness is shown above each bar.

Water entrainment includes both free and emulsified water. The results indicate that more water was entrained together with HydroCal at 10 °C than at 25 °C. This is due to the higher viscosity and slower spreading rates of HydroCal at colder temperature that reduced the contact area of the oil/drum surface, leading to the higher amount of recovered liquids. This effect was especially pronounced for HydroCal recovery at 10 °C in a 10 mm oil slick. The net oil recovery was higher at lower temperatures, but there was a significant increase in water entrainment.

An important difference in the emulsification behavior of Endicott and HydroCal was observed during the tests. Endicott did not emulsify as much as HydroCal. In most cases, the water content of the recovered Endicott emulsion was less than 15%, while the HydroCal emulsion contained up to 30% water. The emulsification of HydroCal was especially rapid for thin oil slicks and at high drum rotational speeds. Emulsification can also be due to the pump (in this case a hydraulic pump), but we did not conduct experiments to determine the relative contributions from pump and drum. The diesel emulsion contained less than 12% water. In the case of diesel and HydroCal, the amount of entrained water (Fig. 2 and 3) corresponds mostly to emulsified water, since only a relatively small amount of free water

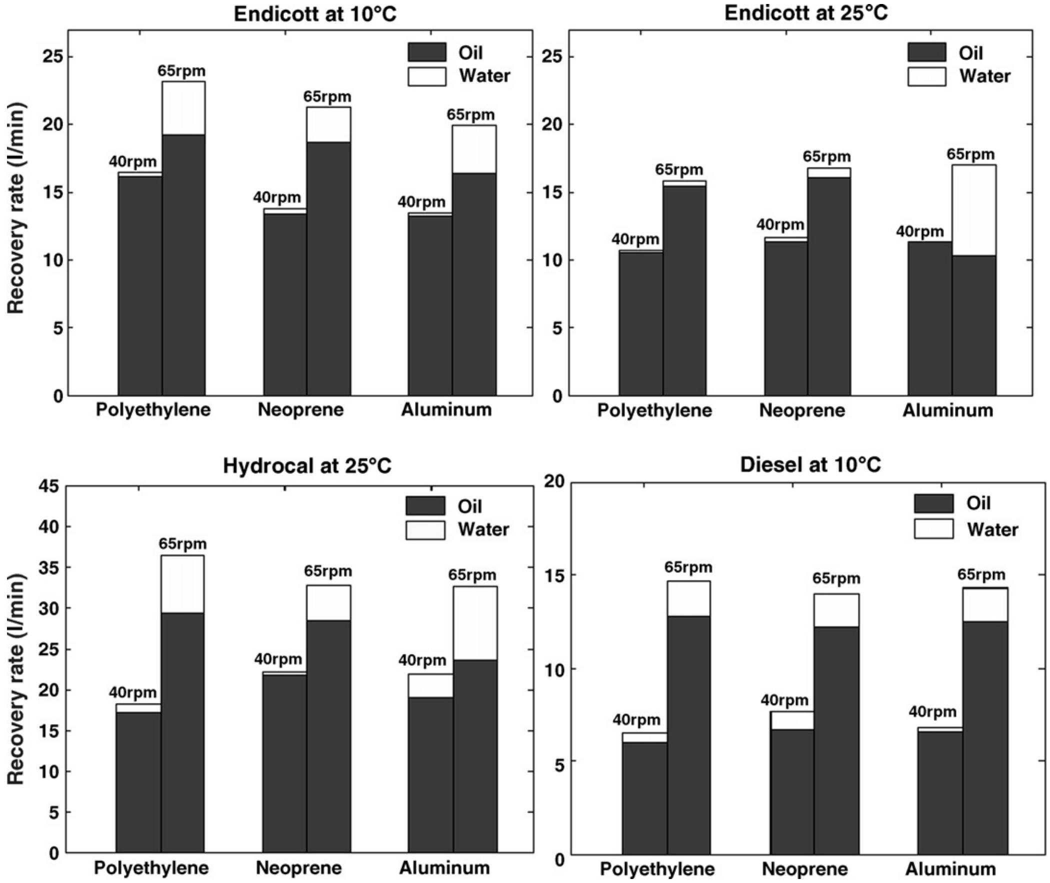

Fig. 3. A comparison of the product (oil and water) recovered by various drums at 40 and 65 rpm. Oil slick thickness was 25 mm for all tests.

was collected. In the case of Endicott, comparable volumes of both free and emulsified water were entrained. The difference in free and emulsified volumes of recovered water was too small to be shown separately in the figures.

Fig. 3 compares the recovery rates and composition of the recovered product at 40 and 65 rpm drum rotational speeds. The results show that the amount of recovered oil can be increased up to 50–100% by using higher rotational speeds. The amount of entrained water will also increase, especially in the case of thin oil slicks and/or viscous oils.

The experiments demonstrated the importance of drum rotational speed on the recovery rates. For any given period of time, the amount of recovered oil increases with increasing rotational speed. However, at higher speeds there is a significant amount of free and emulsified water in the recovered product. If onboard storage space is limited, a lower rotational speed should be selected in order to reduce the amount of entrained free water, unless it can be treated before being discharged. For the skimmer configuration and oils tested, 40 rpm seemed to be near the optimal rotational speed above which the drum starts to entrain significant amounts of free water, and also results in less emulsification (Fig. 4). The slight decrease in the recovery rates at the highest recovery rates in some tests (Fig. 4) is due to a higher amount of free water picked up by the drum at higher speeds, which was subtracted from the total volume of the recovered product thereby decreasing the net amount of recovered oil. The rotational speed must be adjusted to the recovery conditions. As the oil slick gets thinner, the drum should be slowed down to reduce free water entrainment. If storage capacity is not limited, or if an oil–water separation mechanism is available on-site, drums should be operated at their maximum speed.

The experiments have shown that there is a difference between the recovery rates of drums made of various materials. In the case of thicker oil slick and low viscosity oil, the Neoprene drum was slightly more efficient than aluminum or polyethylene drums (Fig. 4). For 25 and 50 mm oil slicks, the difference between materials was about 20%. The difference between materials was much more pronounced in the case of a 10 mm oil slick (Fig. 5). For these thin slicks, polyethylene was found to be the most efficient recovery surface. While Neoprene can recover oil more efficiently from thicker slicks due to its surface structure, it was less efficient for thin slicks and more viscous oils.

In Figs. 6–9, we present the net oil recovery rates for only one material (aluminum) to illustrate the effect of temperature, oil properties and slick thickness on the amount of collected oil. A comparison of the effects of oil type, oil spill thickness, and drum rotational speed on the recovery rates is summarized in Fig. 6. It was found that the increase of HydroCal slick thickness at 25 °C from 25 to 50 mm did not lead to an increase in the recovery rates (Fig. 6). A slight decrease in the observed recovery rates can be explained by the fact that oil used for this test was slightly emulsified and contained 6% water. This amount of water was subtracted from the total amount of recovered fluid

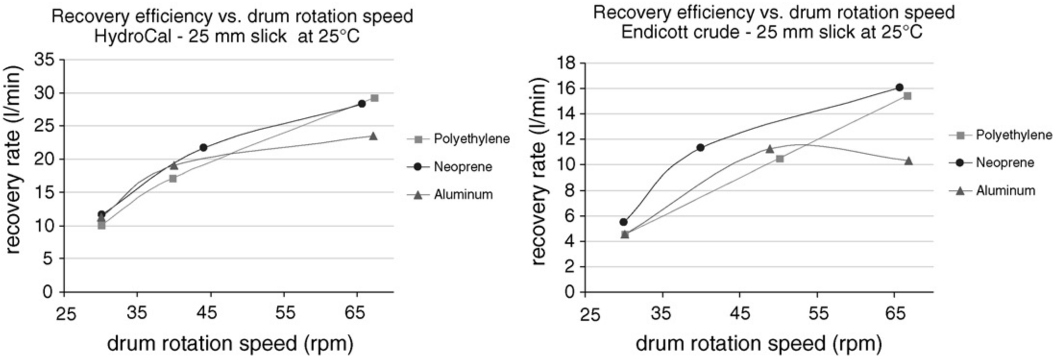

Fig. 4. Net recovery rates as a function of drum rotational speed at 25 °C, for a 25 mm oil slick thickness and different drum materials.

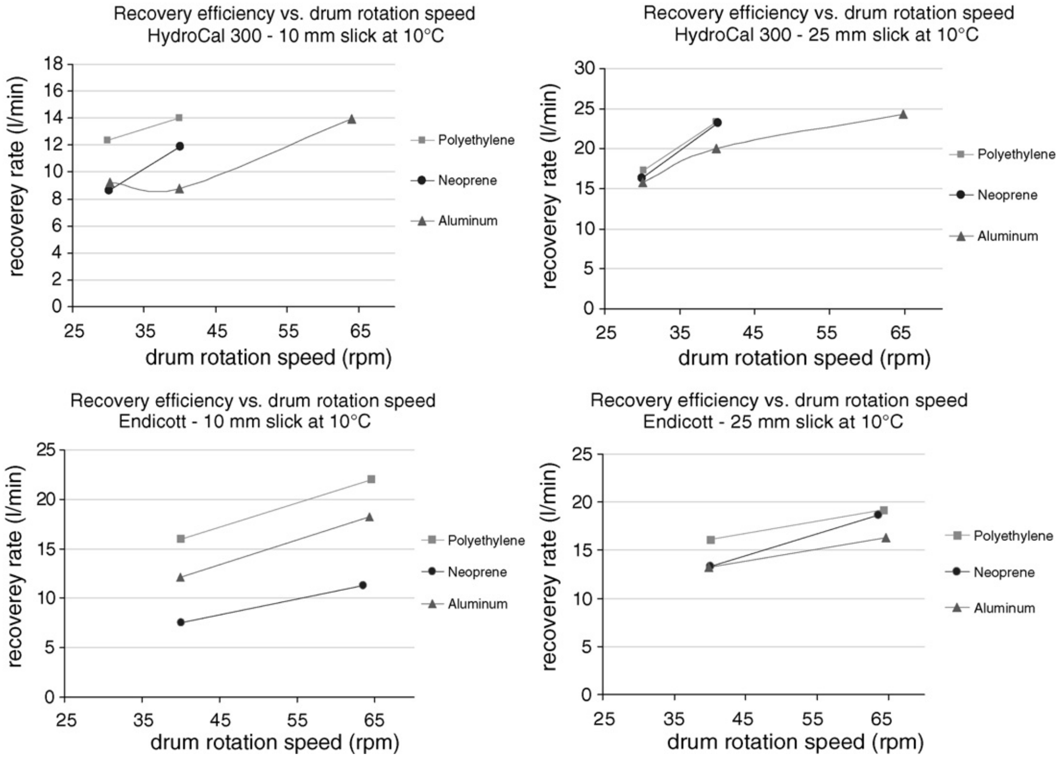

Fig. 5. Net recovery rates as a function of drum rotational speed at 10 °C, for different oil slick thicknesses and drum materials.

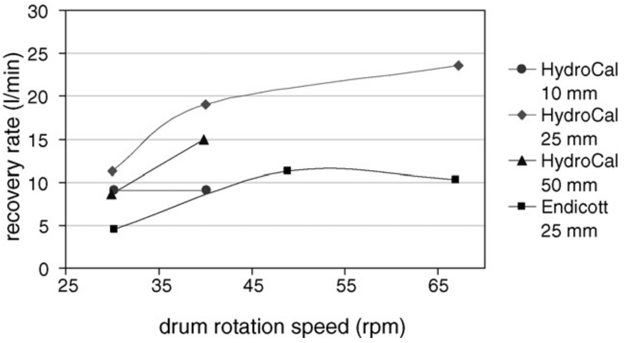

Fig. 6. Net oil recovery rates of aluminum drums at 25–30 °C.

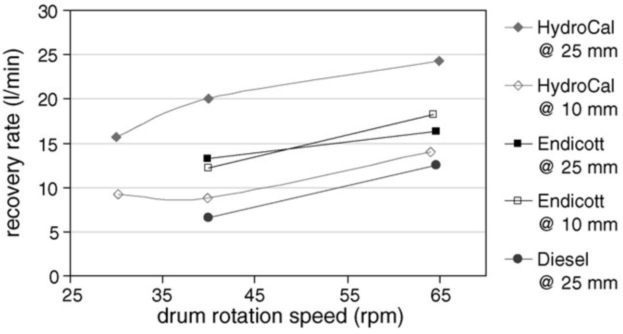

Fig. 7. Net oil recovery rates of aluminum drums at 10–15 °C at different drum rotational speeds and oil slick thicknesses.

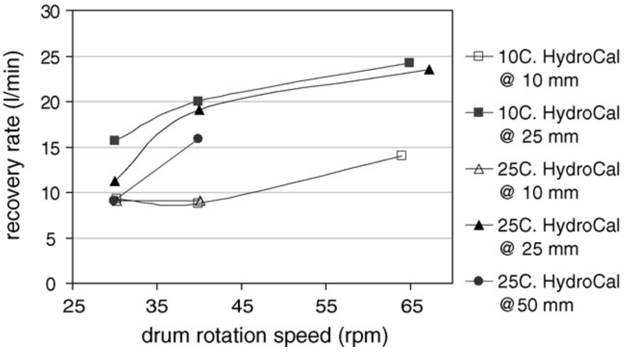

Fig. 8. Effect of temperature, oil slick thickness and drum rotational speed on the net oil recovery rates of HydroCal using aluminum drums.

together with water collected during the experiments, consequently reducing the amount of recovered oil. The decrease in oil slick thickness from 25 to 10 mm led to a significant decrease in HydroCal recovery, particularly at higher speeds. More free water is entrained in thin oil slicks, which can be compensated by reducing the rotational speed. It is therefore important to maintain a reasonably thick oil slick during the recovery operation to avoid water entrainment or a decrease in oil recovery rates.

Fig. 7 presents the recovery rates of aluminum drums tested during the second test at 10–15 °C. It is interesting to note the difference in the amount of recovered Endicott oil between the first and second tests (Figs. 6 and 7). At the warmer temperatures (25–30 °C), the recovery rates were in the range of 11–15 l/min. This value increased to 13–18 l/min at the lower temperature (10–15 °C) during the second test. Thus, temperature alone can significantly influence oil recovery, due to the effect on oil viscosity. Although the decrease of oil slick thickness had a significant effect on the recovery rates of HydroCal under all conditions, it had very little effect on the recovery rates of Endicott oil during the second test series (Fig. 7).

For a 25 mm slick thickness, the recovery rates of the more viscous HydroCal was higher than for Endicott due to the thicker oil film withdrawn by the drum. At 10–15 °C and 10 mm slick thickness, the recovery rates of HydroCal was lower than for Endicott, which may be explained by the significant increase in viscosity of HydroCal at lower temperatures. At this small oil slick thickness, water can contact the drum at various points, reducing the total contact area between oil and drum. Due to the much higher viscosity, HydroCal is not able to spread as fast on the drum surface as Endicott, leading to a higher amount of entrained water and a reduction in oil recovery rates. In addition, the HydroCal in these tests contained up to 5.5% of emulsified water since it quickly emulsifies during the test. The higher amount of water in the emulsified oil was subtracted together with water collected during the test from the total volume of the recovered product. Fig. 2 shows that the volume of total recovered liquids was slightly higher for HydroCal than for Endicott oil at 10 °C and 10 mm slick thickness, but a significant amount of water was within the oil.

The recovery rates of diesel was the lowest among these oils due to its low viscosity which resulted in a formation of a very thin oil film on the drum allowing for only a small amount of product being withdrawn per every drum revolution (Fig. 7).

The effects of temperature and oil slick thickness on the recovery rates of HydroCal using aluminum drums are summarized in Fig. 8. It was observed that oil slick thickness had a significant effect on the recovery rates of HydroCal, while temperature did not affect the recovery rates substantially. This pattern is opposite from the one observed for Endicott, where the change in temperature had greater effect on the recovery rates than the change in oil slick thickness.

The effects of temperature and oil type on the recovery rates while controlling for oil slick thickness (25 mm) are illustrated in Fig. 9. Recovery rates of Endicott oil were inversely proportional to the ambient temperature, while the recovery rates of HydroCal were not significantly affected by temperature.

Through these different tests it became clear that oil viscosity is a major factor in oil recovery using drum skimmers, but that the relationship is not always the same. Thus, in Fig. 10 the effect of oil viscosity on the recovery rates is examined for aluminum drums. The three oils are plotted here at two temperatures, generating a range of oil viscosities. The curves show that for a 25 mm slick the recovery rates increase with oil viscosity, reaching a plateau at about 150 mPa s. Increasing drum rotational speed from 40 to 65 rpm at this oil thickness can increase the net oil recovery rate by up to 20%. For the 10 mm slick, the recovery rates decreased with increased viscosity but also reached a plateau at around 150 mPa s. At this thickness, the recovery rates were directly proportional to oil viscosity. This

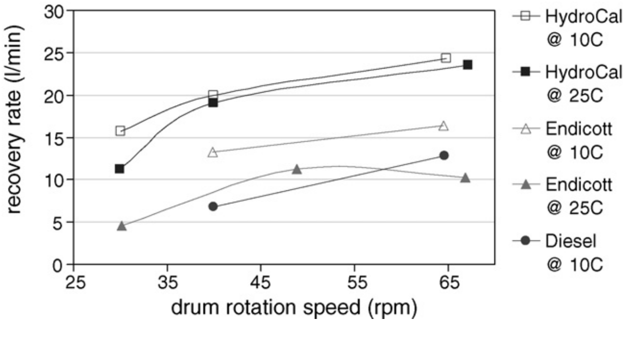

Fig. 9. Effect of oil type and temperature on the recovery rates of various oils, for aluminum drums in a 25 mm oil slick.

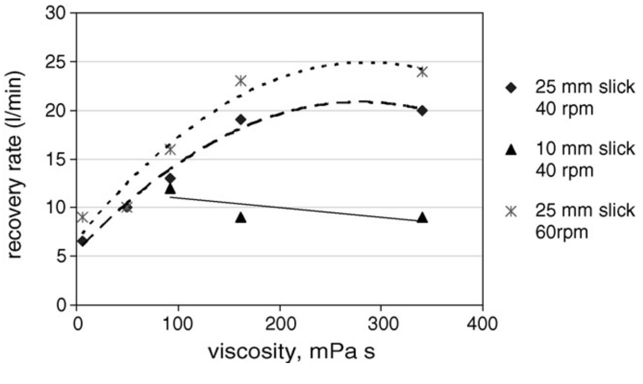

Fig. 10. Effect of oil viscosity on oil recovery rates using aluminum drums.

can be explained by decreased coverage of the drum surface by the oil as viscosity increases, since the oil is unable to spread on the surface fast enough to cover it all. In this case, water has a larger contact area with recovery unit decreasing the amount of collected oil. This graph can thus be used to predict the recovery rates of different oils under various conditions if similar size drum is used.

4. Conclusions

The full-scale oil spill recovery tests with oleophilic drum skimmer showed that:

- The material on the recovery surface can affect the recovery rates. For a thicker oil slick and low viscosity oil, the Neoprene drum was slightly more efficient than aluminum or polyethylene drums. For 25 and 50 mm oil slicks, the difference between materials was about 20%. The difference between materials was much more pronounced in the case of 10 mm oil slick (up to 100%). For thin slicks, polyethylene was found to be most efficient as it entrained the least amount of water in most cases.
- Recovery rates are significantly influenced by the viscosity of oil. For thicker oil slicks, recovery rate increases with viscosity but appears to reach an asymptotic value at around 150 mPa s. For thinner oil slicks, recovery rate appears to decrease with viscosity, within the range of observed viscosities.
- Oil slick thickness has a significant effect on recovery rates. An increase in oil thickness from 10 to 25 mm led to two to three times higher recovery rates for HydroCal oil. An increase from 25 to 50 mm did not significantly increase the recovery rates. The amount of entrained free water was typically higher for 10 mm oil thickness than for the 25 or 50 mm oil thickness. Endicott oil recovery rates were found to be less sensitive to changes in oil thickness than HydroCal, due to its lower viscosity.
- A lower temperature increases the recovery rates of Endicott oil by increasing its viscosity and allowing for a thicker oil film to form on the recovery surface after withdrawal. The more viscous HydroCal oil recovery was a stronger function of oil slick thickness than temperature.
- Drum rotational speed had a significant effect on the recovery rates. For the particular skimmer and a dram type tested, 40 rpm appeared to be a nearly optimal rotational speed in most of cases. Beyond 40 rpm, the dram started to entrain significant amounts of free water. It has to be noted, however, that free water was the only limiting factor. If a response team is not concerned with free water in the recovered product, the maximum rotational speed should be used to recover more oil.

Acknowledgements

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