

Improved Mechanical Oil Spill Recovery Using an Optimized Geometry for the Skimmer Surface

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The primary objective of this research was to improve the efficiency of mechanical oil spill response equipment by optimizing the geometry of the oleophilic skimmer recovery surface. Another objective of this work was to study the relation between the operational variables and the oil spill recovery efficiency in a full-scale oil spill recovery test, comparing novel and conventional oleophilic drum skimmer configurations. The study showed that using the new surface pattern in the recovery unit can increase the skimmer oil recovery efficiency up to three times. The improved surface pattern was found to be efficient on oils with a wide range of viscosities, including diesel oil, which is a challenging liquid to recover due to its low viscosity. The effect of the surface pattern dimensions on the recovery efficiency was explored. Guidelines for the design of a more efficient surface geometry tailored to the properties of the recovered oil were developed.

Introduction

Oleophilic skimmers are the most used type of mechanical oil spill response equipment. They operate on the principle of oil adhesion to a rotating surface. The rotating surface lifts oil out of the water to an oil removal device (e.g., scraper, roller, etc.), which then transfers it into a collector. When employed on a large scale, mechanical recovery may be very time-consuming and expensive due to its low recovery rates. Recovery rates of adhesion skimmers range between $0.2 \text{ m}^3/\text{h}$ for diesel oil and $50 \text{ m}^3/\text{h}$ for heavy crude (1). A more efficient recovery device can thus reduce the time and cost of the cleanup and prevent significant environmental damage.

Various shapes of the recovery unit, such as a mop, belt, brush, disc, and drum, have been developed to increase skimmer efficiency. The low recovery rates of the smooth drum, belt, and disk skimmers can be explained by their relatively small surface area. Only a limited amount of oil adheres to the recovery surface in every rotation, requiring a large number of skimmers and longer operation time to increase the overall recovery efficiency. Brush and mop skimmers attempt to address this issue by introducing bristles to the recovery surface and therefore increase the surface area in contact with oil. Although these skimmers allow more oil to adhere to the recovery surface, not all the adhered oil can be removed from the bristles by the scraper, especially when recovering lighter oils. Thus, a significant fraction of the oil remains on the bristles and returns back to the slick, reducing the overall recovery efficiency.

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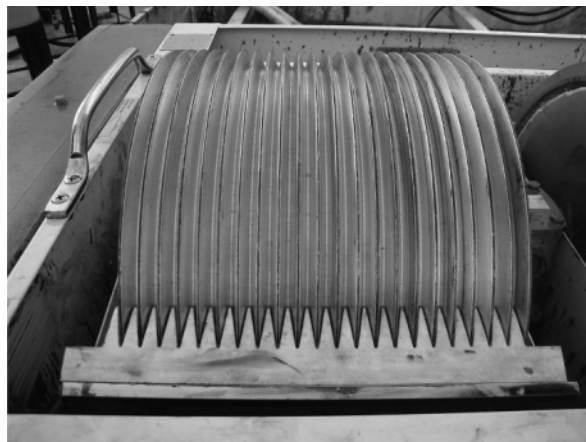


FIGURE 1. Grooved drum with the matching scraper installed into a skimmer frame.

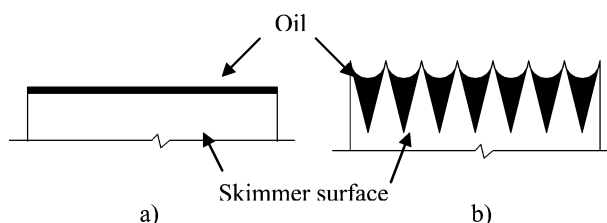


FIGURE 2. Cross-section of recovered oil film in case of (a) smooth surface and (b) grooved surface.

We developed a novel pattern for the recovery surface that can significantly increase the recovery efficiency of an oil skimmer. The basic configuration of the patterned recovery surface in a drum skimmer, as well as matching scraper, is shown in Figure 1. This pattern is composed of a series of triangular-shaped grooves in the direction of rotation of the recovery unit. The scraper can be machined to almost perfectly match the recovery surface. Thus, close to 100% of the adhered oil can be removed and transferred into the oil collector in every rotation.

This pattern maximizes the surface area of a drum, belt, or disc skimmer. Depending on the angle and depth of the channels, the surface area can be increased several-fold for the same width of recovery surface. It also allows menisci to be formed in the depth of the channel, increasing the amount of recovered oil and slowing down oil drainage. Thus, the overall volume of recovered oil is much higher for a grooved surface than for a smooth one, as illustrated in Figure 2.

The area inside the grooves available for oil collection per 1 m of recovery surface as a function of groove depth is presented in Figure 3. The total area inside the grooves is independent of the groove angle. The number of grooves per unit width of the recovery surface is inversely proportional to the groove angle; thus, the total groove area is constant for any given groove depth. Figure 3 shows that the deeper the groove is, the larger the area available for oil collection inside the groove is. It must be noted though, that during the recovery process, oil may not occupy the entire area available inside the groove.

The groove configuration can be tailored to the properties of recovered product to increase oil recovery efficiency. For lighter oils that only use the deep part of the groove, a surface with a larger number of shallow narrow grooves, which creates a larger number of menisci, will increase efficiency. For more viscous oils, deeper and wider grooves will be more

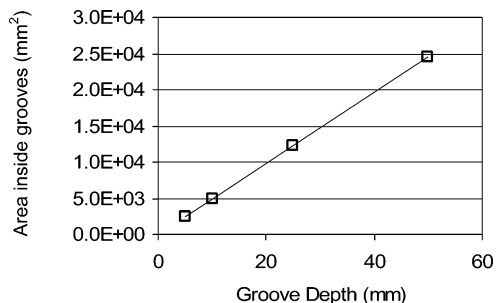


FIGURE 3. Area inside all grooves located in 1 m of the recovery surface as a function of groove angle and depth.

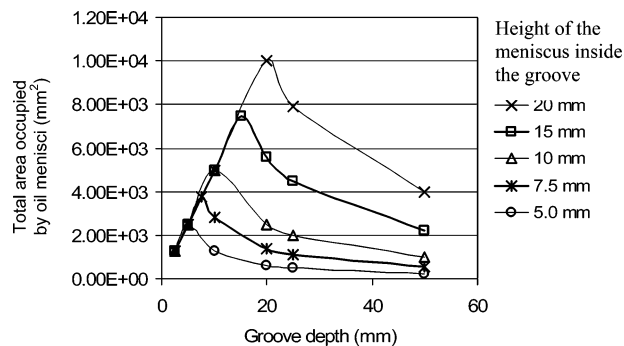


FIGURE 4. Total area occupied by oil menisci in all grooves located in 1 m of the recovery surface as a function of groove depth and meniscus height.

efficient. The total area occupied by oil menisci inside all the grooves located per 1 m of recovery surface is plotted as a function of groove depth and meniscus height. Figure 4 shows that if the size of the groove is equal or close to the height of the meniscus inside the groove, the oil slick will occupy the maximum area on the recovery surface, and hence, maximum recovery can be achieved.

A number of studies have tested the recovery efficiency of various skimmers (2–13). These studies compared the recovery rates of various skimmers but did not evaluate or report the influence of operational parameters such as spill thickness, surface pattern, ambient temperature, or drum rotation speed on oil recovery efficiency. The skimmers tested in these studies had different configurations, dimensions, capacities, and recovery modes. In most cases, several operational parameters were changed simultaneously for each test, making it difficult to distinguish the effect of each variable separately. The current study specifically evaluated both design and operational parameters independently, thus providing key information on the influence of these parameters about the overall oil recovery efficiency.

Field Tests at Ohmsett

Field scale tests were performed at Ohmsett, the National Oil Spill Response Test Facility, located in Leonardo, New Jersey. Ohmsett is the world's largest tow/wave tank operated and maintained by the U.S. Department of the Interior, Minerals Management Service (MMS). A number of drums were manufactured and retrofitted on 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 efficiency was evaluated.

The major test variables were as follows: (a) surface pattern of the recovery surface (smooth and grooved drums); (b) oil type (diesel, Endicott—Alaskan crude oil, and HydroCal 300 lubricant oil); (c) oil slick thickness (10, 25, and 50 mm); (d) drum rotation speed (30, 40, and 65 rpm); and (e) ambient temperature (10–15 and 25–30 °C).

TABLE 1. Properties of Oils Used in Ohmsett Field Tests

oil type/temp	density (kg/m ³)		viscosity (mPa·s)		asphaltenes %
	15 °C	25 °C	15 °C	25 °C	
Diesel	833	823	6	2	0
Endicott	923	907	92	50	4
HydroCal 300	921	905	340	162	0

Test Drums. Four interchangeable drums were manufactured from aluminum. Two smooth drums had a width of 25.4 cm and a diameter of 35.6 cm. Two other drums had a novel pattern composed of 2.54 cm deep grooves with a 30° groove angle machined onto the surface of the drum. The grooved drums had a width of 25.4 cm and a diameter of 39 cm. A scraper was made to match the grooved pattern. Figure 1 illustrates a grooved drum installed in the skimmer body.

A frame-type drum skimmer (Elastec Minimax) was used during this test. The standard configuration of this skimmer was composed of a smooth drum rotating through the oil layer. The adhered oil was subsequently removed by a plastic blade to an onboard recovery sump. Grooved drums were manufactured to the physical specifications of standard Elastec drums so that they could be interchanged in the skimmer frame.

Test Oils. Diesel, Endicott (an Alaskan crude oil), and HydroCal 300 (a lubricant oil) were used in this test to evaluate the effect of oil properties on the recovery efficiency by smooth and grooved drums. These oils have significantly different properties (Table 1), which allowed us to test the recovery surfaces in a wide range of possible recovery conditions. Diesel was only tested during the second test series, at colder temperatures, since it was added later to the protocol.

Test Protocol. The tests at Ohmsett were carried out in two separate test series. The first test series was conducted in August 2005 at an average ambient temperature of about 25–30 °C. The second test series was completed in October 2005 at an average ambient temperature of about 10–15 °C. The objective was to simulate an oil spill under warm and cold water conditions and to determine the effect of temperature and oil viscosity on overall oil spill recovery efficiency. The experimental setup and experimental procedure is described in detail in ref 14. The test protocol can be summarized as follows.

The skimmer assembly was secured in the center of the test tank filled with seawater located on the deck of the Ohmsett facility. A known amount of oil was added to the test tank to establish a desired slick thickness. The slick thickness was maintained constant throughout the test. This was achieved by adding fresh oil to the test tank at the same rate as it was recovered by the skimmer. Three rotational speeds (30, 40, and 65 rpm) were used for 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 but also more water was collected particularly for thinner oil slicks (10 mm). Entrained water consisted of both free and emulsified water. Higher emulsification rates were observed at higher rotational speeds.

At the end of each test run, the total amount of fluids (oil and water) was measured. Then water was 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. By subtracting the amount of free and emulsified water from the volume of total recovered product, the net amount of recovered oil was

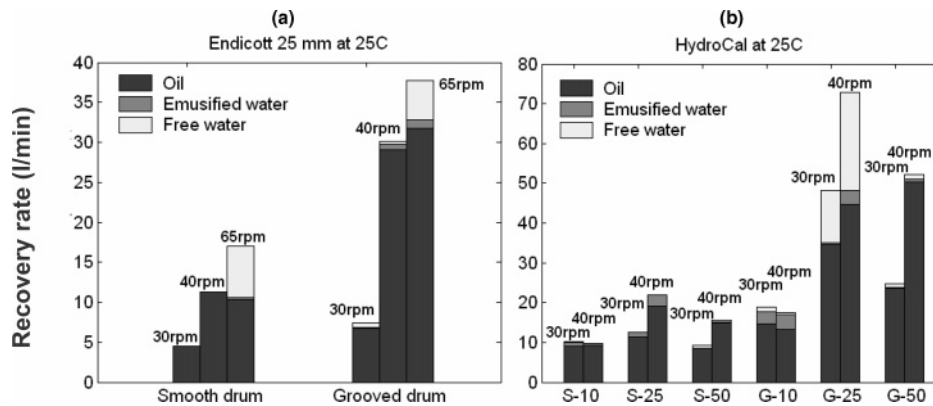


FIGURE 5. Recovery rates of oil and free and emulsified water at 25–30 °C, for (a) Endicott oil and (b) HydroCal oil.

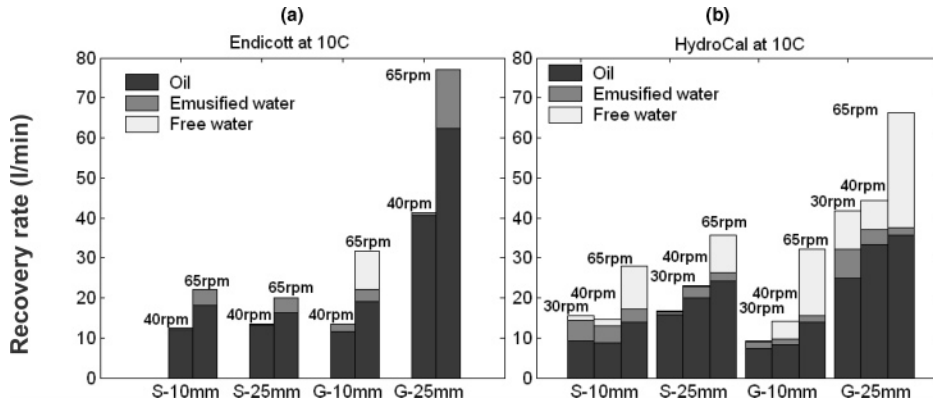


FIGURE 6. Recovery rates of oil and free and emulsified water at 10–15 °C, for (a) Endicott oil and (b) HydroCal oil.

determined. The recovery rate was determined by dividing net recovered oil by the duration of the recovery test.

Test Results. Figure 5 presents the results collected during the first test series at a temperature between 25 and 30 °C, while Figure 6 presents the data collected during the second test series at a temperature between 10 and 15 °C. Both figures show the proportion of oil and water in the recovered product for Endicott oil for a 25 mm oil slick (Figures 5a and 6a) and HydroCal for a 10, 25, and 50 mm oil slick (Figures 5b and 6b). In Figures 5 and 6, the y-axis shows the recovery rates measured in liters per minute. Values on the x-axis refer to smooth or grooved drums at a certain film thickness. S-10/25/50 refers to a smooth aluminum drum, while G-10/25/50 refers to a grooved aluminum drum tested with a 10, 25, or 50 mm slick. The drum rotational speeds are indicated above each bar. Free water refers to the amount of free water in the recovered product. This volume was found by subtracting the volume of fluid after decanting from the volume of total recovered product. Emulsified water refers to the amount of water emulsified in recovered oil that remained after decanting. The water content of the emulsion was determined at the Ohmsett laboratory. Recovery rates were calculated based on the volume of recovered oil after the volume of free and emulsified water was subtracted.

Data presented in Figure 5a indicate that for Endicott oil, grooved drums were up to three times more efficient than smooth drums at a given speed. The difference was especially pronounced at higher rotational speeds. The amount of entrained water was comparable for both drum configurations. Data for HydroCal oil in Figure 5b show that while the recovery efficiency of the grooved drums was only about 20% higher for a 10 mm slick, it was two times higher for 25 and 50 mm slicks. These results also indicate that grooved drums can be efficiently used with oils of various viscosities. Although they are especially efficient at higher speeds and film thicknesses, their performance on thin slicks at lower

drum speeds is similar or slightly higher than the recovery efficiency of smooth drums.

Figure 5b shows that an increase of oil slick thickness from 10 to 25 mm led to about a 100% increase of recovered oil volume (at 40 rpm) by the smooth drum and up to 200% increase of recovered oil volume (at 40 rpm) by the grooved drum. The increase of oil slick thickness from 25 to 50 mm significantly decreased the amount of collected water but did not lead to an increase in the amount of recovered oil. Grooved drums appear to be especially sensitive to changes in slick thickness. For a 10 mm slick and 10 °C, the recovery efficiency of HydroCal by the grooved drums was similar to the efficiency of smooth drums (Figure 6b). For a 25 mm slick, the recovery efficiency of grooved drums increased up to 50%.

The amount of entrained water for Endicott oil was similar for smooth and grooved drums. In the case of HydroCal, grooved drums entrained between 25 and 600% more water than smooth ones. Although grooved drums tended to entrain a higher amount of water than smooth drums (Figures 5 and 6), the amount of water entrained in the G-25 tests presented in Figure 5b seems to be particular to this test. This could be due to the difference between the behavior of Endicott and HydroCal oil. HydroCal emulsified much more rapidly than other tested oils leading to the formation of water-in-oil emulsion during the preliminary phase when recovered oil was returned back to the test tank. Thus, some tests (e.g., G-25) were performed with test oil that contained a significant amount of emulsified water.

Figure 5 shows that the amount of recovered oil as well as entrained water is proportional to the drum speed except for the thin 10 mm HydroCal slick (S-10 and G-10), the increase in drum speed from 30 to 40 rpm did not lead to any significant changes in the amount of recovered product. For thicker slicks, the increase in drum rotation speed led to a 25–50% increase in the amount of recovered

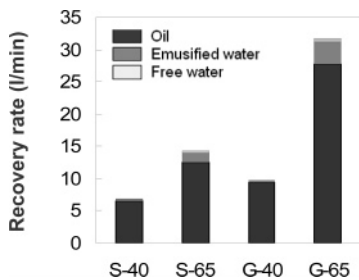


FIGURE 7. Recovery rates of diesel oil and free and emulsified water at 10–15 °C for the 25 mm slick.

product. It was observed that for the drums and oils tested, 40 rpm was nearly an optimum operational speed, above which water entrainment became significant. Rotational speeds below 40 rpm were found to be less efficient for oil recovery.

Figure 6 represents the analysis of results collected during the second test series at temperatures between 10 and 15 °C. Data from this second test series show similar trends to the results from the first test series at 25–30 °C. Grooved drums were two to three times more efficient in recovering Endicott for a 25 mm slick. Their efficiency was similar to smooth drums for a 10 mm slick. At 10–15 °C, the recovery efficiency of HydroCal was lower than that for Endicott. This can be explained by the much higher viscosity of HydroCal at this temperature. Because of its higher viscosity, HydroCal was not able to displace water in the bottom of the groove, thereby reducing the total contact area between the oil and the drum surface. HydroCal was not able to spread as fast at the drum surface as Endicott did and had a lower access to the drum, which led to a higher amount of entrained water and reduced overall recovery efficiency.

Figure 6 shows that the increase of drum rotational speed increased the amount of collected product (both oil and water). Grooved drums were extremely efficient on thick oil slicks; however, for 10 mm slicks, their recovery rates were similar to those of smooth drums. It was observed in most cases that when the drum was operated at low rotational speeds, water was collected in the form of an emulsion. At higher rotation speeds, water was collected as free water. Grooved drums collected more free water, while water collected by the smooth drums was in the form of an emulsion. It must be noted that the oil emulsification rate was not only determined by the drum geometry but also by the total amount of entrained water by a given drum since oil also emulsified as it was conveyed through the transfer lines and pumps, particularly for the higher recovery rates.

Figure 7 shows the amount of recovered diesel, as well as the entrained water in those tests. The recovery rate of diesel was the lowest among the tested oils due to its low viscosity. Low viscosity resulted in the formation of a very thin oil film on the drum surface, resulting in only a small amount of product withdrawn in every drum rotation. Diesel oil emulsified rapidly, and thus, most of the collected water was in the form of an emulsion. Because of its rapid emulsification, the tests were performed with diesel that had a water content of up to 3%. At 40 rpm, the recovery efficiency of smooth and grooved drums was similar. At higher speeds, grooved drums recovered up to 100% more oil than smooth drums.

Figure 8 illustrates the effect of oil viscosity on the net recovery efficiency. The recovery efficiencies of all tested oils at both temperatures are plotted against viscosity without differentiating between oil types. At 10 mm thickness and 40 rpm, we observed the lowest recovery rates for both smooth and grooved drums (triangles). In most cases, regardless of surface geometry, one can observe an initial increase in net recovery rates. Past that point, the recovery efficiency begins to plateau or decrease with increasing viscosity. Viscous oils

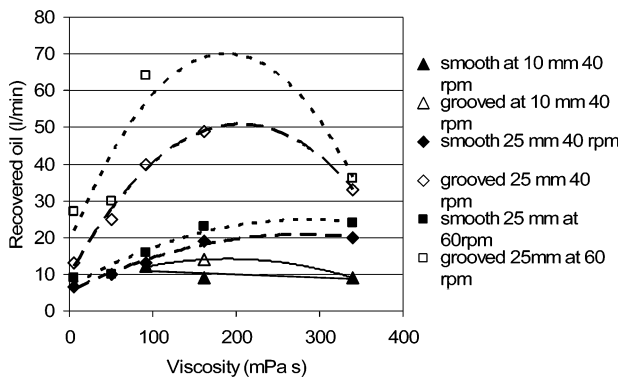


FIGURE 8. Effect of oil viscosity on the net recovery efficiency for smooth and groove drums.

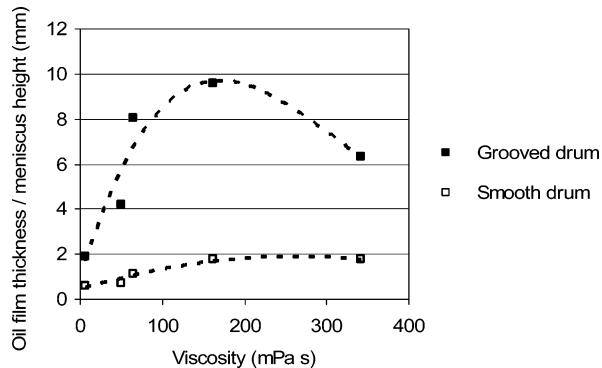


FIGURE 9. Effect of oil viscosity on the thickness of the oil film recovered by a smooth drum and height of the meniscus inside the groove (30°, 25.4 mm deep) on the grooved drum.

have lower spreading rates, allowing water to come into contact with the recovery surface and decreasing the amount of collected oil. This behavior was especially pronounced in the case of grooved drums.

At 25 mm slick thickness and 40 rpm rotation speed, the recovery efficiency increased for both smooth (◆) and grooved drums (◇). The recovery efficiency at the same film thickness and drum rotation speed of 65 rpm is shown by squares. The data show that for smooth drums in a 25 mm slick, the recovery efficiency increases with increasing oil viscosity until it reaches a plateau at about 250 mPa s. For the grooved drums tested, the recovery efficiency reaches a maximum at about 200 mPa s and then decreases due to lower oil spreading rates caused by higher viscosity. Although a decrease in the recovery efficiency was observed for more viscous oils, grooved drums still recovered significantly more oil than smooth drums.

The results presented in Figure 8 would be different if drums of other diameters or geometries were used. Nevertheless, it gives a general illustration of the viscosity–recovery efficiency relation for smooth and grooved drums and allows responders to estimate the recovery efficiency based on the viscosity of the oil of interest. The data suggest that if the groove dimensions are tailored based on the oil properties, even higher recovery efficiencies can be achieved. Grooved drums with shallow narrow grooves can be used to recover light oils, while wider and deeper grooves would improve recovery efficiency of heavier oils.

Figure 9 along with Figure 4 provides an example of the groove size optimization analysis performed for the groove configuration used in this study. In Figure 9, the height of the oil meniscus inside each 30° groove is plotted against the oil viscosity along with the oil film thickness on the smooth drum. The height of the meniscus and the film thickness was estimated based on the volume of oil recovered in the field

tests during each drum rotation normalized by drum surface area and surface geometry.

Figure 9 shows that the height of the oil meniscus in the groove is up to four times higher than the thickness of the oil film recovered by the smooth drum. For Endicott oil (50–100 mPa s), the height of the meniscus was estimated to be in the range of 6–8 mm. One of the curves in Figure 4 corresponds to the total groove area occupied by the meniscus filling each groove with a height of 7.5 mm. This case is very similar to the recovery of Endicott oil. Figure 4 shows that for the groove configuration tested (30° groove and 25.4 mm deep), only one-third of the available groove area is occupied by the meniscus. Figure 4 also suggests that for Endicott oil and a 30° groove angle, the optimum groove depth yielding to the maximum area occupied by the meniscus, and hence, higher recovery efficiency, is 6–8 mm. This analysis shows that the groove pattern used in this study can be efficiently used on viscous and emulsified oils but could be modified to achieve maximum recovery of oils with low viscosities. Following these guidelines, equipment manufacturers can manufacture, and oil spill responders can select, the most efficient drum configuration tailored to the properties of the oils they intend to recover.

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