A MINI REVIEW OF USING OLEOPHILIC SKIMMERS FOR OIL SPILL RECOVERY

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1. INTRODUCTION

Always, oil spills are considered as the most threat and the most dangerous effects on the sea ecosystems, social economy, and environment. Up to now, oil spills have been known as originated from the maritime operation, oilrig drilling, natural incidents and other [1,2]. An oil spill incident of Deepwater Horizon occurred in 2010 that was considered as the biggest one in the history is an example [3]. The latest incident of oil spills involving Iranian oil tanker, which sank off the Shanghai shore on 16 January 2018, carried around 1 million oil barrels. In another situation in the US, on 23 June 2018, there were thousands of crude oil gallons leaked into the river due to a train accident related to coming off the tracks [4]. As mentioned oil spill incidents have been negatively and seriously affecting the human and animal life, as well as ecological systems and environment [5]. The spilled oil quantity and the affected area by oil spill incident need a well-prepared scheme/plan and a proper selection regarding the technique of oil spill cleanup to assure rapid and effective recovery. Reality showed that the response to the oil spill was relatively successful depending on the existence of effective recovery methods. To do this, besides the as-established techniques, the selection of the most suitable equipment for the anticipated range of weather and sea (such as wave height, current speed) conditions, types of spilled oil, the possible effects on marine organisms are extremely necessary. Therefore, a great need for cleanup solutions based on effective cost, fast duration to minimize the impacts of oil spills is an extremely important task.

There are many various methods for petroleum removal from oil spill incidents, being thermal-, physical-, chemical-, biological- and mechanical techniques [6]. Each method showed the advantages regarding the oil spill recovery capacity (OSRC), however, the selection of initial methods for oil recovery from big oil spills is very necessary [7]. Normally, the methods with high OSRC are used first because the higher the recovered oil spill volume is, the lower the negative effects are [8]. Mostly, physical-, chemical-, and biological techniques are usually applied to the treatment of oil spill incidents [3]. Meanwhile, thermal techniques are rarely used due to the huge emitted pollutant into the environment [9].

On the contrary, mechanical techniques show high OSRC and can be used for small-to-large-scale incidents, although the disadvantages of these methods such as time-consuming, many equipment, large manpower, and expensive cost were also reported [10].

The design of skimmers is used on the basis of the adhesive property of their surfaces aiming at recovering oil spill from seawater surface. Normally, oleophilic skimmers are classified in a configuration such as a disk skimmer, belt skimmer, brush skimmer, and drum skimmer. Regarding the drum skimmer, it is submerged only in part below the interface surface of the oil-water, oil is recovered by a scraper into a collector through the principle of adhering to the surface of the drum when the drum skimmer is rotated through the oil spill. A group researchers has presented the deep studies on improving the performance of disk skimmers [11,12]. Recently, in the research of Hammoud and Khalil, they have reported experimental study results on the hydrodynamics of two types of skimmers, being disk skimmer and belt skimmer [13]. The skimmer based on the drum was considered as a first mechanical method, which was the simplest, although published information about the performance of drum skimmer is only received the limitation. The drum skimmer can be used to recover not only oil but also the mixture of oil-water from the seawater surface. Environment Canada has carried out an experiment on counter-rotating drums [14]. This device was used to study the influence of the drum rotation speed and the gap between the drums on the capacity of spilled oil recovery. As a result, the optimal drum speeds were found greater than 10 rpm and a minor effect of gap width between the drums on the oil spill recovery was indicated. In a study of Tsukuba Institute Ship and Ocean Foundation, an experimental study has conducted for a dual drum skimmer which was considered investigating under the conditions of calm wave and current that was controlled at fixed oil slick thickness [15]. This work was to evaluate the influence of rotation speed of the drum on the rate of oil spill recovery. A relationship between the rate of oil spill recovery and the drum rotation speed and the viscosity of spilled oil was concluded. Besides, the rate of oil spill recovery was proportional to the oil thickness and the current velocity.

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Nonetheless, the rate of oil spill recovery was inversely proportional to the wave height. Finally, this study has indicated that the double drum offered a larger surface for skimming, thus, the rate of oil spill recovery increased. In another study, the performance of both single drum skimmer and double drum skimmer has investigated experimentally for emulsified and non-emulsified oils [16]. An important conclusion has given with the dependence of the performance of oil spill recovery on a large number of parameters. Thus, it resulted in the more thorough investigation of the effect of parameters on the oil spill recovery capacity. Although the oil spill recovery capacity was appreciated, the working process of skimmers should be supported by booms, which were used to zone the oil spill area. The combination of booms and skimmers aiming at meeting efficiently the chain prevention-to-recovery was reported [17]. Furthermore, the available studies were carried out on the basis of commercial oils aiming at the comprehensive evaluation.

2. CLASSIFICATION OF SKIMMERS

Mechanical technique-based oil spill recovery has demonstrated to be an effective cleanup strategy [18]. Using countermeasures for oil spill recovery much depends on the weather conditions. Generally, the OSRC is inversely proportional to wind and wave speed [19]. A review in literature was carried out to evaluate the relationship of the performance of all countermeasures (%) related to oil recovery and various weather conditions (wind speed m/s), this relationship is shown in Figure 1.

![Figure 1: The effect of wind speed on countermeasures](image)

Figure 1 shows that relative effectiveness of methods using skimmers and booms reaches a high value at low speed of wind (< 15m/s). However, booms are usually used to zone the spilled oil before using another main method such as skimmers, in-situ burning or sorbent materials. Boom is a mechanical device acting as a barrier to aim at preventing the oil from spilling and diverting on the water surface. On the basic structure, booms include 4 main parts such as float, freeboard, skirt and ballast (Figure 2). Above parts are durably linked together to withstand the horizontal load produced by waves because booms suffer from waves, winds, and currents more than any other equipment in oil spill treatment technique [20]. Normally, booms are divided into 3 types including fence, curtain and rope, and its effective length is around 15m [21]. (c) Oleophilic skimmer

| Table 1: Boom-use classification based on freeboard and total height |
|-----------------------|------------------|------------------|
| Service | Total height (inches) | Freeboard (inches) |
| Calm water | 6 - 12 | 4 - 10 |
| Harbor | 12 - 24 | 10 - 18 |
| Offshore | > 4 | > 8 |

Fence booms (FB) fabricated by rigid or semi-rigid materials are designed with the floating fence-like structures aiming to maintain 60% of the height of FB under the seawater. In order to easily facilitate for fabrication, installation and linking the sections of FB to become a desired length, the length of each boom section is usually 15m [22]. Some researchers have indicated the advantages of FB such as minimal storage space, easy-handling, and higher reliability [23]. However, drawbacks of FB including low stability and flexibility in strong waves and winds have also reported by OSS [24]. Curtain booms (CB) based on impervious materials and floating structures are usually used to circle the oil spill area before considering next recovery methods. Similarly, to FB, CB has a flexible skirt under the water. Normally, the diameter of circle chamber for containing an oil spill is from 100mm to 500mm along with 150-800mm of the skirt length. Besides, some CB characteristics such as higher reliability and higher flexibility in towing compared to FB, and a difficulty in cleaning and storage were presented [23,25]. The fire-resistant boom is known as an efficient method in combination with in-situ burning techniques. This method is thought a great potential with around 1,500 m2 of burn area to protect the shoreline from an oil fire [26]. After zoning by booms, oil spills are recovered by as-mentioned methods. Among the above methods, skimmers show the high OSRC in the calm conditions of weather [6]. Some researchers has indicated that some skimmers could not work effectively in conditions with wave height higher than 1m or current velocity greater than 1 knot [27]. Besides, inefficient operation of most skimmers in ice or debris-containing water was reported [28]. Skimmers are classified in the basis of the operating principle including oleophilic surface, weir, suction/vacuum, elevating, submersion, and vortex/centrifugal skimmers.

![Figure 3: Oleophilic skimmers](image)

Oleophilic surface skimmers (OS) are also considered as sorbent-surface ones and the major skimmer groups. These skimmers are operated when the oils adhere on the surface of devices aiming at removing them from the water [29]. The surface of these skimmer types may be a disc (Figure 3a), drum (Figure 3b), rope (Figure 3c), or belt (Figure 3d) that is able to be moved to pass the oil on the water surface. After that, roller or a wiper blade is used to produce the pressure for removing the oil. As-removed oil is pumped and led to the storage tank.

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Rest skimmer types show the suitable characteristics for each specific situation. Weir skimmers (WS) based on gravity are used to recover oil from the water surface after that oil is drained and is moved to a submerged holding tank. A major drawback of WS is a problem related to rock back in the choppy water that occurs due to wave suction in the air above the oil slick layer and below the water surface [30]. Thus, it results in increasing water amount and decreasing the recovered oil amount. To avoid the recovered amount of water, advancing weir with self-leveling features and adjustable characteristic of depths is more suitable than the stationary model. As reported, these skimmers showed the highest efficiency when worked in low debris water, but they showed the highest effectiveness in recovering oil spills of very heavy oils or tarballs [31]. Suction or vacuum skimmers (SVS) work on the vacuum principle or the differential in pressure aiming at removing oil from the surface of the water. Normally, SVS includes a small-floating head that is connected to a vacuum force source from outside, a vacuum truck is an example. These SVSs also show the same tendency as WS, being easy clogging with debris [32]. Although there is a restricted use to light-to-medium oils for SVSs, the suction skimmer is considered as the most economical one. Meanwhile, large vacuum skimmer tends to be suitable for larger oil spills than the suction skimmer. Elevating skimmers (ES) act as conveyors to collect oil from the surface of the calm water. The operation of the ES shows inefficient oil recovery with large-debris waters water of rough water. Besides, they are not suitable for light or very heavy oils. Sometimes, they are converted into specialized vessels. Submersion skimmers (SS) are operated in the basis of a belt or inclined plane aiming at forcing the water under the surface [33]. The advantages of SS are moving faster than other skimmers; thus, they can cover a large spilled-oil area. However, they are only suitable for light oils and relatively thin oil slick layer. However, they can be used for shallow waters, and the tolerance of the inclination angle is considered as the biggest disadvantage. Vortex/centrifugal skimmers (VCS) work on the support of centrifugal force. Oil and water is drawn along with the increase in the thickness of oil film [43]. The results from this study showed the increase in ORR along with the increase in the thickness of oil film and the decrease of the inclination angle of the belt. However, the effectiveness of recovered oil increased when the increase in both the inclination angle of the belt and the thickness of oil film, and the decrease of the belt linear speed were considered. The achieved results from other studies also demonstrated the similarity of ORR and ORR for belt skimmer [44-46].

3. EVALUATION OF OIL RECOVERY EFFICIENCY BASED ON OLEOPHILIC SKIMMERS

As-mentioned oil recovery methods based on skimmers collect oil from water surface without dissolving oil into the water. These methods, which are thought as the safest ones for the marine environment, require the right evaluation related to weather conditions, available equipment conditions, and manpower [34]. Besides, the optimal design for skimmers was gotten the especial attention aiming at achieving the maximum of oil recovery rate (ORR). In 1987, has carried out an experimental study based on flow visualization aiming at producing the qualitative information regarding the flow field that was covering the disc skimmer [35]. The oil recovery efficiency was evaluated according to achieved data in case of the oil-only and thin-film conditions. As a result, the maximum performance gained up to 600% depending on operating conditions. However, a multiple-disc structure of skimmers showed interference effects between adjacent discs, resulting in the consideration in the design of practical skimmers. Next experimental studies also were conducted, the same results related to the use of a flow model for evaluation of skimmer characteristics were reported in the literature [30].

Practically, studied the use of disc skimmers for recovering floating oil [11]. A conclusion related to the dependence of OSRC on a large number of parameters of the device was presented, this resulted in a careful investigation of the various parameters before giving the specific evaluation of ORR and efficiency of the device. A group researcher has investigated the effect of the novel parameter on the performance of disk skimmers [36]. The results showed that nearly-doubled increase in ORR were received when the angle between the drum and the vertical plane was optimized. Besides, the optimal rotating speed was found as about 80 rpm. Especially, with 20mm of oil-film thickness and as-studied largest disk diameter, the OSRC was reached 204%. Recently, fabricated a rotating disc and belt skimmer that was worked on energy supplied by solar panels to recover oil from the water [37]. The result achieved from this study showed that more than 90% of spilled oil was recovered by using an as-fabricated skimmer. The experimental studies on disc skimmers can be found in reference [38].

In another study, the ORR from a drum skimmer was investigated on the basis of the effects of some factors such as structure and design factors, and operating conditions [39]. Four oil types, being crude oil, diesel oil, SAE 10W oil and SAE 140W oil were used for this study. As a result, an increase in ORR was proportional to the increase in diameter, length and center height of the drum. However, this efficiency tended to inversely proportional to oil viscosity, surface tension, and density. In addition, an empirical equation for the prediction of ORR was proposed. The similar evaluation related to the optimal design of drum skimmers to get the high OSRC can be found in the literature [16,40,41].

A group researcher has set up an experiment with a simple blanket belt skimmer based on two factors: low cost and available device [42]. Two oil samples with different physical properties were used for evaluating. The result showed that the OSRCs of 190/1h and 253/1h for above two-oil samples were collected by the as-used constructed device and the cost was minimal. In another study regarding belt skimmer, some researchers has also indicated the dependence of the belt skimmer performance on various operating parameters which showed the speed and inclination angle of the belt, and the thickness of oil film [43]. The results from this study showed the increase in ORR along with the increase in the thickness of oil film and the decrease of the inclination angle of the belt. However, the effectiveness of recovered oil increased when the increase in both the inclination angle of the belt and the thickness of oil film, and the decrease of the belt linear speed were considered. The achieved results from other studies also demonstrated the similarity of ORR and ORR for belt skimmer [44-46].

Some researchers has reported and demonstrated a novel, efficient-, economical device for oil spill collection based on physical principle, being the discovery of Torricelli and Pascal’s and Archimedes’ law, which has never been applied to skimmers and so-called “passive oil collection device” [47]. The study results showed the advantages of this novel skimmer including environmentally friendly, durable, economical, no-noise and no-pollution characteristics. The as-designed 10m oil collector (Figure 6) could recover at least ten times compared to the best skimmer, meanwhile, a minimal energy consumption (100 times smaller than that of other) was also presented. Besides, the manual instruction for installing this novel skimmer on the vessels was carefully introduced in the study.

In a detailed evaluation of the effects of material on the recovery surface, oil viscosity, oil slick thickness, temperature, and drum rotational speed on OSRC were conducted [48]. As a result, polyethylene for fabrication of the recovery surface, oil viscosity around 150mPa.s, 10-25mm of oil thickness, an increase in ORR at low temperature, the rotational speed of drum of 40rpm showed the maximum of OSRC.

In a project of Coastal Response Research Center, material selection for fabrication of novel skimmer (Figure 5) was conducted [49]. In this study, material selection has based on historical practice, price and availability, without the adhesive properties because there was very little effort to study the affinity of new materials for oil recovery under cold conditions. Research conducted in the laboratory has indicated that the recovery material on the skimmer surface could change the recovery efficiency up to 20%, and higher recovery efficiency, even up to 200%, could be achieved as the geometry of the skimmer surface was tailored. The tests for this skimmer was conducted at Ohmsett – The National Oil Spill Response Test Facility. After taking the tests for 3 different materials for V-patterned drums compared to the conventional smooth drums which were studied by Broje et al [48] have shown. Achieved results were illustrated in Figure 6 which showed the relationship between different materials on the drum surface and oil recovery efficiency.

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In addition, using hydrodynamic simulation for optimization of oil skimmer can be also available in reference [50]. The technical parameters related to skimmers are given in Table 2.

| Skimmer Type     | Wind Velocity (knots) | Current Velocity (knots) | Wave Height (m) | Oil Viscosity (cSt) | Sensitivity to Debris | Recovery Efficiency (%) | Nominal Recovery Rate (m³/h) |
|------------------|-----------------------|--------------------------|----------------|---------------------|-----------------------|------------------------|-----------------------------|
| Oleophilic Drum  | 10                    | 1.0                      | 1.2            | 30,000              | Medium                | 50 - 90                | 1 - 60                      |
| Oleophilic Disc  | 10                    | 1.0                      | 1.2            | 3,300               | Medium                | 50 - 90                | 1 - 400                     |
| Oleophilic Belt  | 6                     | 1.0                      | 1.2            | 1,000               | Medium                | 50 - 90                | 10 - 400                    |
| Oleophilic Rope  | 10                    | 1.0                      | 1.2            | 20,000              | Medium                | 50 - 90                | 1 - 50                      |

It can be seen from Table 2 that the oil recovery efficiency of oleophilic skimmers can reach 90% depending on the weather conditions. However, in the calm water and wind, belt or disc skimmer should be used to get the maximal recovery rate. For oil spills with high viscosity, drum skimmer show more suitable than the rest.

4. CONCLUSIONS

Based on the review analysis of using oleophilic skimmers in oil spill recovery strategy, it can be seen that it is safer to avoid the oil spill incidents than to deal with the consequences of oil spills. The combination methods based on booms and mechanical equipment are considered as the useful solutions for recovery of oil spills with high yield. However, the selection of suitable equipment according to weather conditions (sea state, current velocity), type of spilled oil is extremely important because it relates to the oil recovery efficiency, oil recovery rate, deployment and usage of oil spill-response-equipment. High oil recovery rate will save the time, cost, as well as the negative impacts to the environment. The results of review shows that oleophilic drum skimmer offers a higher oil recovery efficiency (50-90%) with a large range of viscosity.

Meanwhile, oleophilic belt skimmer gives a high oil recovery rate with maximum of 400m³/h although it is only suitable for oil with low viscosity. Generally, the use of the mechanical equipment for oil spill recovery based on oleophilic skimmers needs to be considered thoroughly and rapidly to get the highest oil recovery in the shortest period of time.

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