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EFFECT OF ADHERING SURFACE TYPE OF AN OLEOPHILIC DISK SKIMMER ON THE OIL SPILLS RECOVERY FROM WATER

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ABSTRACT

In the present study, the interaction between a large number of adhering surfaces and spilled oil was experimentally studied throughout an extensive research program aiming toward enhancing the performance of the oleophilic disk skimmers commonly applied for recovery of oil spills from aquatic environment. Therefore, nine kinds of materials with different surface characteristics were devoted as adhering surfaces of disk skimmer to achieve this purpose. Instantly, one of these materials relies not only on adhering the oil to its surface but also on absorbing the oil through its fibrous texture. The study extended to include some other associated parameters into consideration like the rotational speed and the oil film thickness to establish their effect on the performance in connection with the material type variation. It was found that the surface roughness affects potentially the affinity of these surfaces for oil and consequently the adhesion process. The material, which aggregates adhesion and absorption features, proved tremendous recovery performance. However, this was accomplished with the unimportant penalty of increasing the disk driving power. In fact, such material can introduce promising option for augmenting the performance of the current disk skimmers. Hence, the careful selection of surface material is of great importance for optimizing the process of oil spills recovery.

KEYWORDS:

Oleophilic disk skimmers, oil spills, surface material type, oil recovery performance.

INTRODUCTION

Occasionally, due to many expected or unexpected reasons in aquatic environment oil spills, originated from petroleum or non-petroleum sources, take place. They leave behind a considerable amount of oil or oil-derived products to leak into waterways. Oil spills are considered as one of the major hazardous sources to pollute the environment. They have numerous drawbacks that impact both human and marine life and put them in danger. Therefore, oil spills should be prevented or fought and get rid of at any cost just they happen. For this purpose, a particular branch of environmental science is already founded dedicating toward facing such a problem. Indeed, many researchers belonging to various specialized fields are potentially associated to set assembled scenarios, what are so-called contingency plans. In particular, contingency plans are a set of flexible and organized actions and just follow the announcement of oil spill incidence. They include in their observation, the acts of defining the applicable response system for each particular situation and then deciding how they will be controlled, the valid cleanup technique, and the nature of the desired logistic support. Of course, each item in such plans and the entire scenarios should be thoroughly prepared, put into consideration every trivial point, and well tested. In fact, a detailed description on this topic is reported in [1-5].

Thus, a vital item in the contingency plan is the appropriate selection of the cleanup approach, that should be applied, to get rid of the oil spills from water. Currently, numerous concepts are potentially presented for this purpose such as; mechanical skimmers, adding chemical or biological agents, so called synthetic or natural sorbents, and in-situ burning. Of course, the key features standing behind deciding the proper means are mainly dependent upon the bounded circumstances of each case such as site of the oil spill, oil quantity, oil type and nature, weather conditions, etc. These concepts were comprehensively surveyed providing crucial discussions and comparisons of their performance and applicability [6-12].

On one hand, in all of the abovementioned concepts, the mechanical, particularly the oleophilic-based, techniques are the most commonly preferred. This is due to their attractive advantages which are characterized with over other means. The literatures [6-8] showed that these techniques have no impact on the environment where no strange hazardous agents or additives are applied. Also, no harmful combustion products may be released as a result of burning the spilled oil in-situ. Nevertheless, the recovered oil could be potentially reused again after undergoing finite number of handling processes.

On the other hand, the principal disadvantage, which they are suffering from, is their limited recovery rate, especially when they are in use on a large scale. Then, the cleanup budget would become improperly expensive in order to minimize its time. Otherwise, elongating the period of remaining the spilled oil in water would lead to the evolution of many out of control dangerous occasions. Thus, improving the performance significantly is crucial issue for such oleophilic means and most of the investigations are thoroughly oriented toward accomplishing this target. Instantly, disk, drum, and belt skimmers are examples which underlay the category of oleophilic means. Many investigators engaged themselves to enhance their performance by concentrating on the effect of varying many parameters of various design and operating conditions, such as [13-19].

In fact, oleophilic skimmers are some kinds of turning devices with superficial surfaces of non-polar, hydrophobic materials and are partially immersed through the spilled oil film and the underneath water. Thus, the oil adheres preferentially to their surfaces. By turning the device, the adhered oil is dragged out of the water. Subsequently, the adhered oil is continuously wiped or scraped off from the surfaces by using mechanical scrapers for further treating process [7]. Therefore, it is obvious that the interactive adhesion surface is the most critical element in such cleanup systems as it remarkably governs their performance. Many engineering materials are commonly devoted for this purpose such as aluminum, steel, and commercial plastics. Peculiarly, the choice of these engineering materials was based on reasons other than the oil affinity and adhesion to their surfaces. Price, availability, and background experience are some of them.

In an attempt to understand the interfacial interaction when oil is brought into contact with a solid surface, Broje and Keller [20] decided that wetting, spreading and adhesion processes are inherently established and then described its behavior. They expressed these processes in terms of the historical contact angles that are created when any liquid approaches a solid surface and can be calculated through the surface forces equilibrium equation (Young's equation) [21]. In general, smaller contact angles indicate larger affinity of the surface for the liquid, in turn, well better wetting and spreading.

The contact angle which is measured and then calculated by Young's equation is well-known as the static contact angle. In fact, the way how the static contact angle is measured in practice, makes it inadequate to represent the wetting and spreading processes. Furthermore, it fails entirely to predict the adhesion property [20]. Therefore, Broje and Keller [20] suggested the application of the dynamic contact angle, instead. It can be measured by using the Wilhelmy plate technique which is based on the Young's modified equation or Wilhelmy's equation [21]. Throughout, recording the contact angle hysteresis curve, resulting from the exerted force variation produced by the moving advanced and receding contact angles, the dynamic contact angle and thus the wetting and spreading processes, could be accurately identified. The adhesion property is represented by determining the mass of the remaining adhered oil on the tested material sample at the end of each run, per unit surface area. Indeed, by using this technique the effect of local composition and surface textural imperfections are eliminated. In more recent work Keller et al. [21] showed that the dynamic contact angle depends on both the advancing velocity of the tested oil to the examined material sample and the oil viscosity. Jokuty et al. [22] used the same technique of the dip-and-withdraw in previous work to determine the adhesion process in similar way. They carried out their experiments using a wide range of materials and oil types. Their results indicated dependence of the adhesive properties on both types, besides the surface roughness.

In reality, the interpretations of the data resulting from the above experiments should be handled with care, when they are applied to actual oleophilic devices used in the oil spills recovery techniques due to two reasons. Firstly, these experiments lack the dynamic action of the real, moving oleophilic skimmers in practice. Secondly, the entire material samples used in these experiments are conditionally undergone strict cleanup procedures as a preliminary step to define precisely the contact angle. However, in real oleophilic skimmers, the contact angle dependency is important only for the first turn of the almost clean skimmer to examine the affinity of the material to the spilled oil, i.e. the wetting and spreading properties. Afterward, for the second and the subsequent turns, the adhering surfaces are permanently coated with thin oil layer after the wiping process. Undoubtedly, the nature of the surfaces will entirely vary. This result in the recovery process is further ceased to be due to the adhesion actions alone. But, it seems to be closer due to the coherent actions between such a coating layer and the floating spilled oil. Hence, this idea explains the misleading interpretation of the previous results of the contact angle experiments about the material dependency when attempting to extend them into realistic oleophilic skimmers. In fact, it is more convenient to believe that other surface features such as roughness, textural structure and stiffness are, perhaps, of greater importance.

Broje and Keller [19] and Hammoud and Khalil [23] studied the effect of material type on the performance of oleophilic drum and disk skimmers, respectively. While the results on drum skimmers showed insignificant dependency upon the material type, the others on disk skimmers provided sensible variations, particularly, with increasing the disk rotational speed. Unfortunately, no data have been conducted about the features of the various surfaces used in these studies.

Thus, this work, as a part of an integrated research program, intended for studying experimentally the effect of material type on the oleophilic disk skimmer performance under predefined design and operating conditions. Several materials with different surface characteristics were devoted as oil-attracting elements of a rotating disk skimmer to simulate closely the real operating circumstances, particularly, the rapid dynamic action and the permanent wetted surfaces. Also, the results of this study concerned with determining the oil recovery efficiency and the disk driving power in addition to the oil recovery rate to provide an integrated and inclusive image of the performance.

EXPERIMENTAL SETUP AND PROCEDURE

EXPERIMENTAL SETUP

In order to investigate the influence of the performance of oleophilic disk skimmers by the type of the adhering surface material, an experimental setup was built in and then undergone a regular set of tests. Fig. 1 shows a typical photograph of almost the entire test facilities which consist of the oleophilic disk skimmer arrangement, the containment apparatus, and the control and measurement instruments. In some details, nine rigid disks of 406.4 mm in diameter and 6 mm in thickness are individually dedicated in the present study as adhering devices. However, their surfaces are fabricated of different material types. In the following, these disks accompanying with their abbreviations and the manner of their fabrication will be concisely described down in successive order due to increasing their apparent surface roughness which have been classified, in turn, into three subdivisions as smooth, moderately rough and highly rough surfaces:

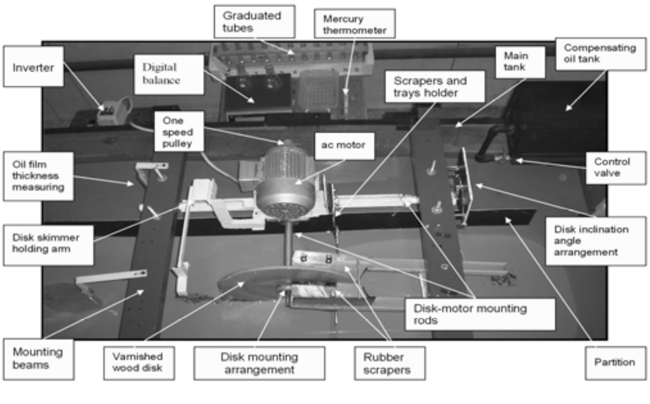


Fig.1 Typical Photograph of the entire experimental setup.

a- Smooth surfaces;

1- Acrylic disk (Acr.), which is machined from one piece of 6 mm in thick acrylic sheet,
2- Thick aluminum foil disk (TAF), which is made of sticking two aluminum foil disks of 0.5 mm in thickness each on both side walls of raw plywood disk of 5 mm in thickness,
3- Varnished plywood disk (VPW), which is prepared by sticking two raw plywood disks of 3 mm in thickness each and then varnishing its side wall surfaces,
4- PVC flooring (top face) disk (PF(TF)), which is made of gluing two PVC flooring (normal smooth top face at outside) disks of 1.5 mm in thickness each on both opposite sides of the walls of raw plywood disk of 3 mm in thickness,

b- Rough surfaces;

5- Raw plywood disk (RPW), which is prepared by sticking two raw plywood disks of 3 mm in thickness each,
6- Sand paper disk (SP), which is made of sticking two sand paper (P400) disks of 0.5 mm in thickness each on both side walls of raw plywood disk of 5 mm in thickness,
7- Plastic screen disk (PS), which is made of gluing two plastic screen (mesh size of 2 mm×2mm) disks of 0.5 mm in thickness each on both side walls of raw plywood disk of 5 mm in thickness,
8- Cutting grinding disk (CG), which is prepared by adhering two cutting grinding wheels of 3 mm in thickness each,

c- Rough-absorbing surface;

9- PVC flooring (fibrous face) disk (PF(FF)), which is made of gluing two PVC flooring (rough fibrous down face at outside) disks of 1.5 mm in thickness each on both opposite sides of the walls of raw plywood disk of 3 mm in thickness.

Eventually, the disk under investigation is firmly assembled at one end of a rotating shaft using special nut and washers arrangement. The other end is driven to rotate by an ac motor via pulleys-belt mechanism. The rotational speed of the electric motor is precisely adjusted to attain any value between stationary and its maximum rate speed (900 rpm) by an electronic inverter (Toshiba, VF−nCIS−2007P). Continuously, the required rotational speed value of the disk is checked, scanned and measured by using a contact/photo tachometer (EXTECH Instruments, 461895) with a resolution of 0.1 rpm in accuracy. The disk-motor system is mounted on a firm arrangement to maintain the disk permanently rotating in a vertical plane with respect to the horizontal reference level. In order to ensure rigid installation, the entire system is suspended into two channel-section beams across the apparatus. They are supported on the top edges of the two opposite and longer sides of a large main reservoir of dimensions 2 × 1 × 0.5 m. It is made of galvanized steel and built within a firm and massive steel frame. The main reservoir is used to simulate the containment system enabling varying the oil film thickness above the surface of water to any desired value. Also, it permits controlling the portion of the disk immersed under the surface of the spilled oil via draining or pumping the water under the oil film through a drain valve located at the bottom of the reservoir. Used SAE40 oil type with physical properties of 891 kg/m^3 in density and 524.77 mPa.s in viscosity is applied in the present investigation as spilled oil.

Two rubber scrapers are installed in firm contact to both sides of disk at its going down part to wipe the dragged out recovered oil into two inclined trays. They direct the recovered oil again into the main reservoir in order to keep almost steady state conditions. Occasionally, however, during the course of measurements of the oil recovery rate (ORR) and the oil recovery efficiency (ORE) in subsequent step, the falling oil from the trays is relevantly directed to gather into a small portable container instead of the main reservoir versus appropriate elapsed time using an accurate digital stopwatch. Afterwards, the net gathered oil is weighed via a precise digital balance (AND) with a readability of ± 0.1 gram.

As a practical and incorporated part of defining the whole performance data, it is convenient to examine the required power to drive the disk skimmer, which can be expressed in proportional with the input power of the electric motor. Initially, the input voltage and current into the electric motor were measured using an accurate digital multimeter. By knowing the power factor (0.75) of the electric motor the input power into the motor can be easily calculated.

EXPERIMENTAL PROCEDURE

At the beginning of each set of experiments, the main reservoir is filled with water up to certain level with its free surface crossing the stationary disk at any two meniscus horizontal lines. A removable scale with 1 mm in accuracy is temporarily attached to the face surface of the disk in a vertical position with its relative zero position the meniscus line. Then, the intended oil under investigation is slowly poured into the reservoir on the water surface to the required oil film thickness (10, 20 or 30 mm) indicated by the close notice of the scale. Afterward, the disk center height distance with respect to the free surface of oil is properly adjusted by filling or emptying the water under the oil film through the drain valve at the bottom of the reservoir. Occasionally, during the oil recovery rate measurement intervals, the valve of the compensating tank with pure oil is regulated to substitute approximately similar amount to that recovered by the disk skimmer.

In next step, the regular experiments are carried out by allowing the disk to rotate at a predefined speed value (ranged between 20 and 120 rpm) by using the inverter and monitoring the tachometer readings. Then, it is left to rotate for at least 30 minutes before commencing any measurements to ensure reaching the steady state conditions. By way, the same has been also done throughout the entire investigation when the speed value is varied. In order to determine the ORR and ORE simultaneously, some amount of the recovered oil mixture is directed to collect in the portable container against the elapsed time. The net mass of the oil mixture is measured by the balance. Then, the mixture recovery rate is calculated by dividing the net mass of the recovered mixture by the registered time. Further, the density of such mixture is identified by reweighing accurately certain well-known volume taken from the same recovered mixture and dividing the resulting measured mass by the predefined volume. By knowing the densities of both the pure oil and water, the value of the mixture density lies in somewhere between the two extreme density values. Then, the ORE is immediately determined by carrying out the interpolation procedure among the three density values by dividing the density difference between the pure water and the recovered mixture by the density difference between the pure water and the pure oil. Obviously, the ORR can easily be calculated as a result of multiplying the measured mixture recovery rate by the calculated ORE. Frequently, ORE and, thus, ORR are alternatively estimated by leaving samples of the collected mixture in long graduated and slender glass tubes for more than 24 hours. The ORE is defined from the ratio between the pure separated oil column height and the total column height in the tube. Well agreement between the two methods was found. For evaluating the random error (repeatability), some of the experiments to calculate ORR and ORE were repeated at least three times and the results were relevantly compared. Measurements were indicated to be accurate within ± 4.2 percent for estimating ORR and ± 5.7 percent for ORE.

During off experiments intervals, the main reservoir is covered to reduce the amount of oil loss throughout the vaporization process and to prevent any strange objects such as dust, debris, insects, and etc. to fall in the reservoir. The present investigation was conducted at an averaged ambient temperature ranged between 22ºC and 28ºC.

RESULTS AND DISCUSSION

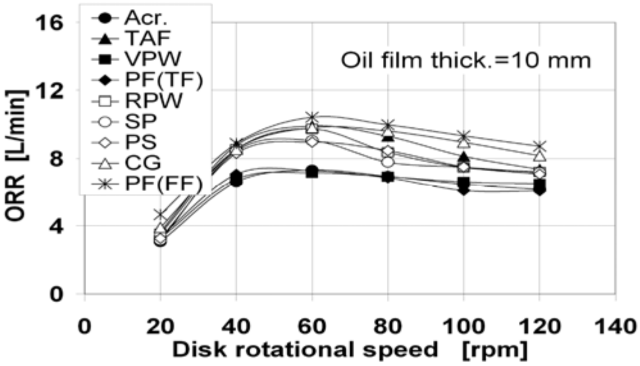
As mentioned before, this investigation is considered as a part of an integrated research project concerning the understanding and developing the operation of oleophilic disk skimmers aiming toward enhancing their performance. Hence, in previous work [24], the performance, in terms of ORR and ORE, of only varnished plywood disk skimmer was comprehensively examined for numerous design and operating parameters. Several concluding remarks were potentially inferred and further implemented during the current study. Thus, the previous work is extended to answer the question of which materials should be an agent as adhering surfaces of the oleophilic disk skimmer, or in other words, how the material type will affect the performance. In the following, the performance data will be expressed again as a function of the disk rotational speed.

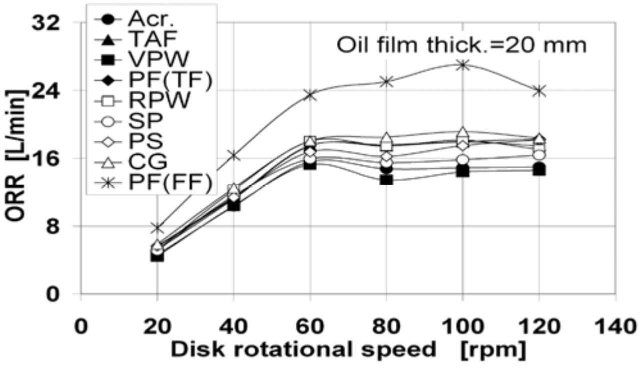
Figs. 2 and 3 show the influence of ORR and ORE, respectively, by the disk surface material type for the same disks geometry, disks center height above oil-water interface (165 mm) and oil type, and for three different values of oil film thickness. Generally, these two figures suggest similar findings to that obtained previously in [24] for varnished plywood material. In some details, the same strictly inherent trends and behaviors of the entire curves for the various studied materials are tremendously obvious. This observation folds on two noteworthy aspects. Firstly, the noticeable consistency among the results curves indicates high degree of confidence in the results of the present investigation. Secondly, all ideas, interpretations, and conclusions can be appropriately repeated as discussed in details by [24]. Concisely, the dependency of both ORR and ORE on the disk rotational speed, the significant augmentation of only ORR with the oil film thickness, and the approach of optimum operating rotational speed and its only dependency upon the oil film thickness are persistently valid.

In particular, Figs. 2 and 3 illustrate that while the ORR results show relative dependency on the material type, the case is not the same with respect to the ORE results, where insignificant dependency would be recognized. Thus, in case of ORR, the differences among the data for each oil film thickness are obvious with varying both the rotational speed and the surface material type. In other words, regarding ORR the smoothest surfaces such as the acrylic, the varnished plywood, and the PVC flooring (top face) have in general less potential than the roughest surfaces such as the cutting grinding and the PVC flooring (fibrous face) for any oil film thickness. These findings can be explained on the basis of the oil tends to penetrate into the channels and cavities due to the nature of the rougher surfaces as described by [20]. Also, it is very interesting to notice here that, the deviations among the ORR values of the different materials are surprisingly reaching their maximum at very close from the optimum rotational speed value corresponding to each oil film thickness.

However, Fig. 2 shows uneven discrepancies in the affinity of each material for the oil, described in terms of ORR, for different values of oil film thickness when attempting to correlate them with the surface roughness. These facts may be more declared by re-plotting Fig. 2 again but this time in column form as shown in Fig. 4. In some details, while some smooth materials (e.g. acrylic, varnished plywood, PVC flooring (upper face)) appear to have low affinity for oil at low oil film thickness, some others (e.g. aluminum foil) have significantly high affinity. Inversely, at larger oil film thickness, it can be noticed that the affinity of the first smooth materials class for oil is enhanced and become better than the second smooth class. That means the differences among them diminish to the degree that their results modified to be negligibly comparable and maybe better. Similarly, in the rough surfaces group, while the least and the highest roughness materials in this group, the raw plywood and cutting grinding respectively, show very promising results for any oil film thickness, the other two remaining materials seem to produce analogous behavior to what was described above for the aluminum foil in the first smooth group.

Therefore, these inconsistencies prove the phenomenological nature of the problem of materials affinity for oils. In fact, many physical properties of the materials and the oils, such as surface roughness, contact angle, surface structure, viscosity, oil nature, etc., and real operating conditions, such as rotational speed, oil film thickness, water existence, interact among them due to very complex interrelated correlations to determine the affinity relationships of different materials for various oils. This demonstrates the fail of all attempts by other investigators to fix strict rules for selecting the optimum material for such assignment. Thus, it is extremely recommended to examine many materials with various properties in different spilled oils in water at real operating conditions and then categorize them due to the preference.





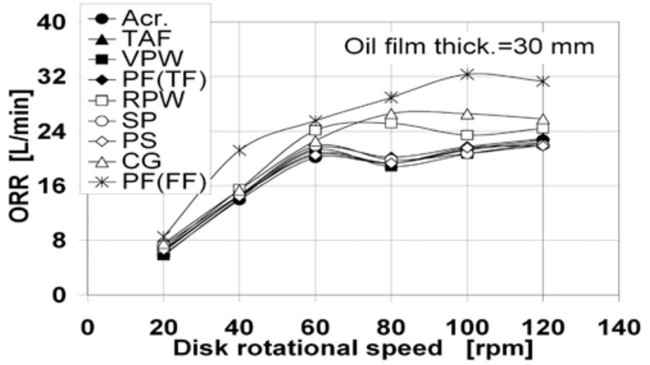


Fig.2 Effect of disk surface material type on the oil recovery rate for various oil film thickness values.

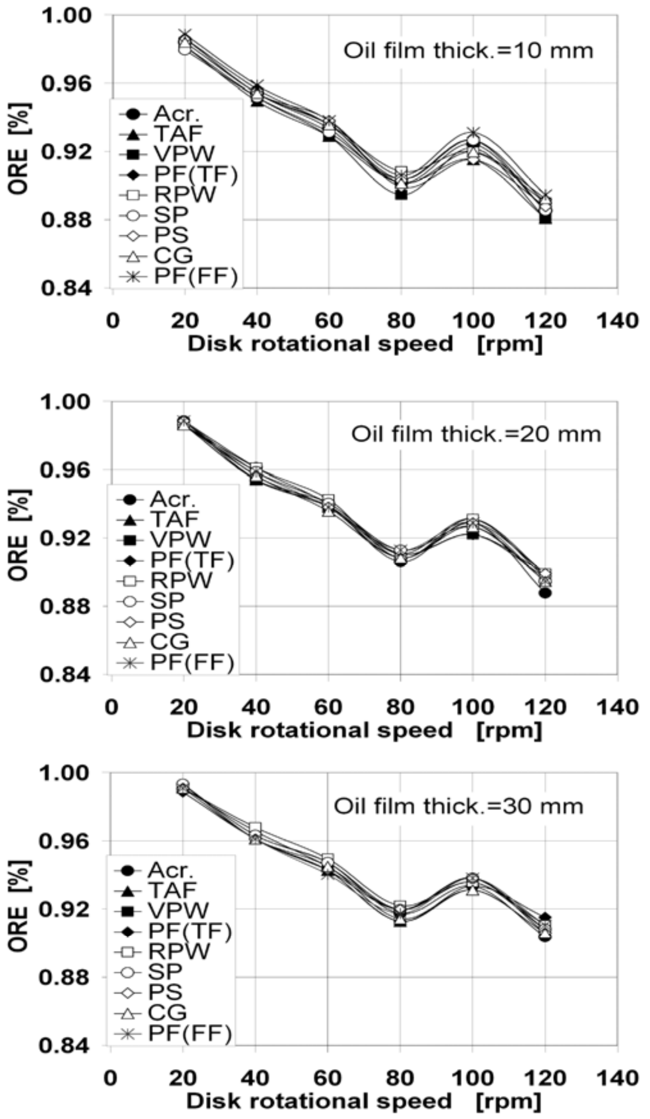


Fig.3 Effect of disk surface material type on the oil recovery efficiency for various oil film thickness values.

Reaching the last group which includes only the PVC flooring (fibrous face), then the increase in ORR becomes substantially remarkable and potentially comparable with other previous ranges, regardless of the oil film thickness. In fact, this material can be considered as the most effective tested material at all, as shown in Figs. 2 and 4. This may be rendered to the fact that this material does not only seem to enjoy with the most apparent surface roughness, but also constitutes in its nature a softy fibrous material. Consequently, the oil recovery is accomplished due to two associated mechanisms.

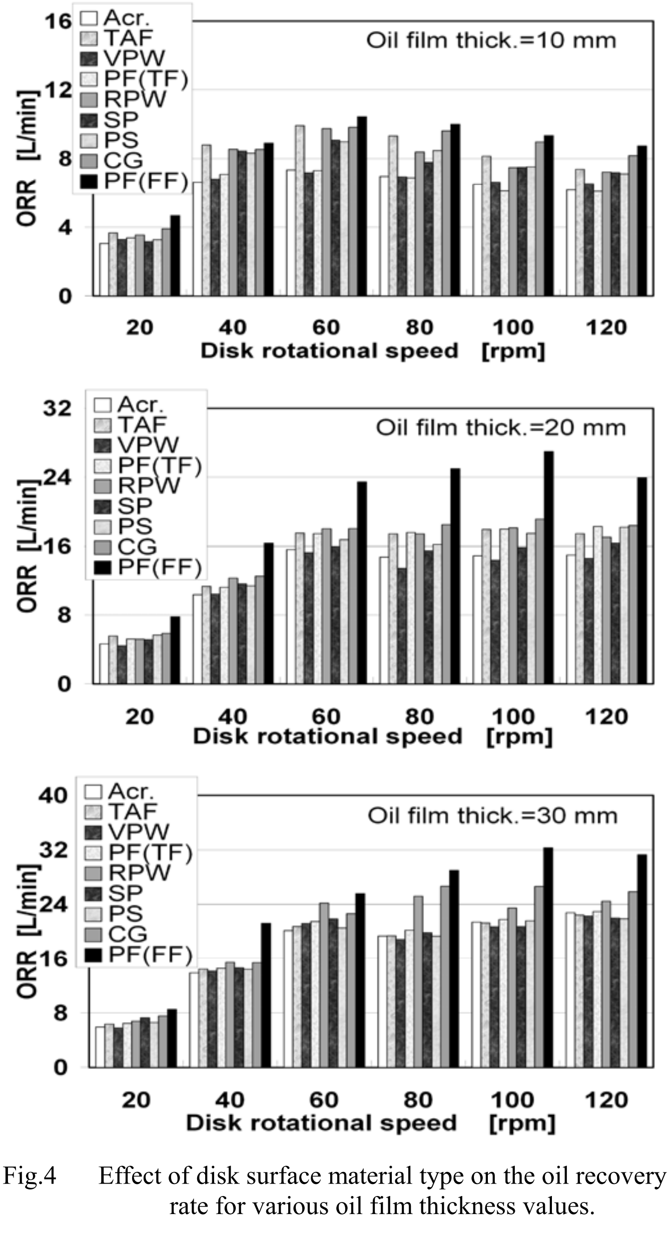


Fig.4 Effect of disk surface material type on the oil recovery rate for various oil film thickness values.

The first is by the adhesion process to the oil-free disk surfaces on the first disk turn and then it follows by the cohesion process to the permanent coated oil layer adhered to its surfaces after the wiping process during the continuous operation. The second is by the absorption process of an additional amount of the spilled oil in its fibrous structure during the recovery stage, which is squeezed out later during the scraping stage.

Noteworthy, this material has other outstanding features in addition to its ORR superiority which can be described by referring to Fig. 3. Obviously, the ORE performance did not degrade as may be wrongly imagined. However, on the contrary, it is generally improved comparing with the other tested materials for any oil film thickness. Particularly, this becomes clear at the optimum rotational speed value corresponding to each oil film thickness. Also, this material was not from the type which experiences permanent swelling characteristic with hydrocarbon oils like rubbers. However, its swelling property was only temporarily during the recovering process. Then, it removes just after the squeezing process. Potentially, these materials can be firmly mounted as a thin layer on the side surfaces of thin and rigid disks that are made of other durable reinforced materials. Therefore, all of these tremendous aspects make this type of materials robust and very interesting to be employed in the field of spilled oils recovery. It is extremely recommended to include many of such materials in individual future study where more tested materials of this type with various geometry and surface characteristics and diverse of fibrous textures subject to further thorough investigations.

Finally, the required power to operate the disk skimmer at some different values of the rotational speed for the various tested materials is shown Fig. 5.

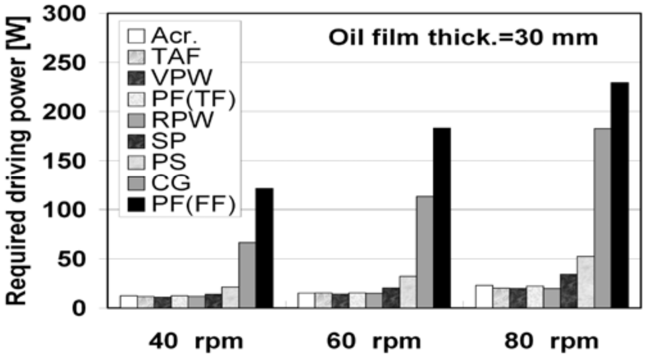


Fig.5 Effect of disk surface material type on the required driving power.

As may be expected, the power is proportional with the apparent surface roughness due to increasing the frictional dissipative effects between the rotating disk and the liquids and at the scraping process. Of course, an additional power is required in case of PVC flooring (fibrous face) to overcome the extra squeezing effects. Therefore, much care should be taken into account while building disk skimmers with such highly roughness and with/without absorbing materials.

CONCLUSIONS

The released conclusions by the present study emphasized on many vital key features aiming toward optimizing the performance of oleophilic disk skimmers, regarding the effect of the disk surface material. They may be carefully extracted and provided as follows:

1. In general, smoother materials have less potential than rougher materials.
2. The problem of affinity of the materials for oils can not be determined throughout individual parameters because it has a phenomenological nature, where it is inherently affected by many interrelated physical properties and accompanying real operating conditions in very complex fashion.
3. Thus, it should be solved by carrying out many parametric studies at simulating realistic operating conditions during the actual oil spills recovery process in practice to categorize the materials into ranks due to their affinity preferences corresponding to the pre-specified operating conditions.
4. Such materials, which aggregate between the adhesion and the absorbing processes, can introduce very promising and highly potential oil recovery surfaces. They provide extraordinary performance findings in both ORR and ORE in comparison with the other only-adhering materials. They seem robust and optimum for any operating conditions. However, special care should be considered while building disk skimmers with these materials due to the experienced excess in the required driving power.

Further, it is recommended to undergo a systematic investigation for optimizing them for other geometries, texture structures, and types.

NOMENCLATURE

D	Disk diameter (mm)
H	Disk center height above oil-water interface (mm)
N	Disk rotational speed (rpm)
ORR	Oil Recovery Rate (l/min)
ORE	Oil Recovery Efficiency (%)
T	Spilled oil film thickness (mm)
µ	Dynamic viscosity of oil (mPa.s)

Acr.	Acrylic disk
TAF	Thick aluminum foil disk
VPW	Varnished plywood disk
PF(TF)	PVC flooring (top face) disk
RPW	Raw plywood disk

SP	Sand paper disk
PS	Plastic screen disk
CG	Cutting grinding disk
PF(FF)	PVC flooring (fibrous face) disk

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