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Investigation of Rotating Disk Skimmer Hydrodynamic Performance during Oil Spills Recovery

دراسة الأداء الهيدروديناميكى للقرص الكاشط الدوار أثناء استرجاع بقع الزيت

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ملخص البحث

نظرا إلى الأهمية الكبيرة للأقراص الكاشطة فى مكافحة بقع الزيت، فإن برنامج بحثي شامل و متكامل قد كرس بغرض فهم السلوك الهيدروديناميكى، و الفيزيائى التي تقف خلفه، وكذلك الخصائص الرئيسية للأقراص الكاشطة أثناء عملية إسترجاع الزيت من على سطح الماء.

و من أجل تحقيق هذا الهدف، فقد أجريت دراسة معملية بارامترية على مجموعة من الأقراص الكاشطة التي تدور فى مستوى رأسي و عمودي على مستوى سطح الماء و الزيت. و لقد تمت التجارب المعملية على العديد من المتغيرات كتصميم القرص الكاشط للزيت و ظروف التشغيل مثل قطر . سمك القرص. سرعته الدورانية. إرتفاع مركزه فوق السطح الفاصل بين الزيت و الماء وكذلك سمك طبقة الزيت و نوع الزيت و ذلك لدراسة تأثيرهم على معدل إسترجاع الزيت و كفاءة إسترجاعه. وقد تم عرض النتائج كدالة فى سرعة القرص الدورانية.

و الدراسة المقدمة تركز على تقييم كفاءة ومعدل إسترجاع الزيت،و التى تعتبرموشر هام عن أداء القرص الكاشط و متغير مهم فى تحديد نوعية الزيت المسترجع و الذى بدوره يلعب دورا هاما فى تحديد أسلوب المعالجة التي تلي عملية الأسترجاع. بالإضافة إلى ذلك،فقد تمت دراسة بصرية للمساعدة فى فهم و تفسير السلوكيات و الإتجاهات المتنوعة لطبقة الزيت و التى قد ظهرت علي نتائج الدراسة البارامترية، حيث وجد الأثنان علي قدر كبير من الأتفاق. عموما، لقد أوضحت النتائج اتفاق كبير مع نتائج الأبحاث السابقة فى هذا المجال. و قد لوحظ أن سرعة الدوران المثالية للقرص تعتمد غالبا على سمك طبقة الزيت المتسرب و التى يصل عندها معدل إسترجاع الزيت إلى أقصي قيمة له عند قيمة مناسبة من كفاءة إسترجاع الزيت. كما اتضح أن زيادة سرعة الدوران تودى إلى نقص كلا الأثنين. بالإضافة إلى ذلك، فقد أوضحت النتائج أن زيادة قطر القرص يحسن معدل إسترجاع الزيت مما يقلل من كفاءة الإسترجاع. فى حين أن، العكس قد لوحظ عند زيادة إرتفاع مركز القرص فوق السطح الفاصل بين الزيت و الماء أو عند زيادة سمك القرص. و أخيرا، فإن الزيادة في كل من لزوجة الزيت أو سمك طبقة الزيت تدعم زيادة كل من معدل و كفاءة إسترجاع الزيت.

Abstract

Due to the great importance of disk skimmers in fighting oil spills, an integrated and comprehensive research program has been devoted intending towards understanding the hydrodynamic behavior, the physics standing behind, and the main features of disk skimmers during the process of oil recovery from water.

In order to achieve the task, extensive parametric experimental investigation has been carried out on disk skimmers rotating in a vertical plane to the oil-water surface. It has been accomplished for a wide range of disk design and operating parameters such as disk diameter, disk thickness, disk rotational speed, disk center height above oil-water interface, spilled oil film thickness, and oil type to study their influence on the oil recovery rate (ORR) and the oil recovery efficiency (ORE). Here, both are entirely expressed as a function of the disk rotational speed and appropriately used as an indicating measure of the performance. In fact, the present work is focused on evaluating ORE, as well as ORR which is the almost only performance parameter reported by other investigators, as an

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important parameter in defining the quality of the recovered oil which plays a significant role in deciding the nature of the handling processes next to the skimming process. In addition, an optical observation study has been performed to help in the interpretation and illustration of the various behaviors and trends appeared on the results figures encountered in the parametric study, wherever a considerable amount of consistency and matching between the two are recognized. Generally, the results revealed reliable good agreement with that obtained previously by other investigators. An optimum disk rotational speed value, which almost depends on the spilled oil film thickness, was noticed where ORR reaches its maximum at an appropriate value of ORE. Any further increase of speed results in a reduction in both. In addition, the results clearly experienced that while an increase in the disk diameter improves ORR, and decreases ORE. However, the inverse was shown for increasing the disk center height above the oil-water interface or the disk thickness. Finally, the increases in either the spilled oil viscosity or the spilled oil film thickness enhance both ORR and ORE.

Keywords: Oil spills; Rotating disk skimmers; Oil recovery rate; Oil recovery efficiency; Environmental Engineering

NOTATIONS

D	disk diameter (mm)
H	disk center height above oil-water interface (mm)
N	disk rotational speed (rpm)
T	spilled oil film thickness (mm)
t	time of oil recovery (sec)
v	kinematic viscosity of oil (m^2/s)
V_{oil}	collected oil volume (L)
ρ_w	water density (Kg/m^3)
ρ_{oil}	pure oil density (Kg/m3)
V_{total}	collected mixture volume (L)
m_{total}	collected mixture weight (Kg)
ρ_{mix}	collected mixture density (Kg/m^3)
ORR	oil Recovery Rate (L/min)
ORE	oil Recovery Efficiency (%)

INTRODUCTION

Nowadays, in order to maintain high standard of living and due to the continuous growing in population, the global demand and consumption of oil-based products, derived either from petroleum or non-petroleum sources, have become remarkably increasingly massive. Usually, they are stored and transported in large volumes. Frequently, during storage or transport, and occasionally as the result of exploration activities, disastrous accidents sometimes happen leaving vast quantities of oils and other oil-based products in behind to spill onto land or into waterways. When this takes place, human health and environmental quality are put at risk. In fact, oil spills endanger public health, imperil drinking water, devastate natural resources, and disrupt the economy. Currently, an abundant number of articles and websites publications are available reporting a detailed historical review on oil spills happened in all over the world during the last few decades, for examples, [1] and [2]. They are concerned with their occurrence sites, their moving path, the spilled quantities and their type, and statistical studies describing their instantaneously direct effects as well as their short- and long-term environmental impact they left on the affected area.

Hence, every effort must be made to prevent oil spills and to clean them up promptly once they occur. In some details, preventing oil spills is the best strategy for avoiding potential damage to human health and the environment. However, once a spill occurs, the best approach for containing and controlling the spill is to respond quickly and in a well-organized manner. A response will be quick and organized if response measures have been planned ahead of time. Therefore, in order to achieve all of these issues, a lot of governmental and non-governmental agencies, societies, organizations, and institutional and research centers were specifically founded around the world and a plenty number of regular and irregular events news, periodicals, and publications were released pointing out the problem of oil spills from many points of view such as [3-11]. The main subjects that were extensively concerned with are outlining and explaining the fate of spilled oil, their potential effects on the environment, involved procedures in controlling oil spills, how they are cleaned up, preparing for oil spills so-called the contingency plans, and organizing the response system for oil spills. Of course, this requires the sharing and collaboration of a lot of scientists and experts groups belong to several specialists' branches.

In particular, when an oil spill takes place, natural actions are always at work in marine and freshwater, both denoted as *aquatic*, environments. These can reduce the severity of an oil spill and accelerate the recovery of an affected area. Some natural actions include weathering, evaporation, oxidation, biodegradation, and emulsification [3]. However, the severity of the impact of an oil spill depends on two main factors. The first is the characteristics of the oil itself. Indeed, each type of oil has distinct physical and chemical properties that affect the way which the oil will spread and break down, the hazard it may pose to aquatic and human life, and the likelihood that it will pose a threat to natural and man-made resources. The second is the natural conditions, such as water temperature and weather that influence the behavior of the oil in aquatic environments [12] and [13].

Thus, just an oil spill occurs on water, two major steps involved in controlling oil spills should be immediately established. They include in order the containment and then the recovery processes. It is critical to contain the spill as quickly as possible in order to minimize danger and potential damage to persons, property, and natural resources. Containment equipment is appropriately used to restrict the spread of oil and to allow for its recovery, removal, or dispersal. The most common type of equipment used to block the spread of oil and concentrate it into one area is floating barriers, called *booms*. Then, once an oil spill has been contained, efforts for cleaning up or removal the oil from the water can begin. Recently, several different concepts and innovative techniques are commonly introduced for this purpose such as; mechanical and oleophilic skimmers, adding chemical or biological agents, so called synthetic or natural sorbents, and in-situ burning. Undoubtedly, a key feature to effectively combating spilled oil is the careful selection and proper use of the equipment and materials most suited to the type of oil and the conditions at the spill site. Many articles, for example [13-20], have currently been available describing these techniques in details and conducting all the required information on their performance, and validity for various locations and operating conditions. Also, they provided thorough comparisons among these techniques indicating the advantages and disadvantages resulting from their application in the treatment of oil spills.

Thus, skimmers are means to recover oil from water based on either mechanical or oleophilic concept. Each type offers distinct advantages and drawbacks depending on the type of oil being cleaned up, the conditions of the sea during cleanup efforts, and the presence of debris in the water [13]. However, oleophilic techniques are potentially characterized by their outstanding flexibility, allowing them to be used effectively on spills of any thickness, by their high oil recovery efficiency and by their neutral impact on surrounding environments over other means [3]. In oleophilic-based techniques non-polar, hydrophobic materials are used in separating the spilled oil from water by adhering the viscous and small contact angle oil into their surfaces leaving the polar large contact angle water [20].

Rotating disk skimmers, in addition to drum, belt, brush, and rope skimmers, belong to this category, where a segment of a hydrophobic-material-made disk is partially submerged in the floating spilled oil film and water. By rotating the disk, the oil is only adhered and then dragged out of water. Subsequently, the adhered oil is continuously wiped or scraped off from the disk surfaces by using mechanical scrapers that are kept in permanent contact to both disk sides. The scraped oil is collected and then pumped into a storage tank system for further following planed recycling and treating processes. In fact, disk skimmers received a lot of concern from many researchers in attempting toward understanding and improving their performance due to their effectiveness and simplicity in operation. In the purpose of evaluating their performance, Hammoud and Khalil [21] carried out extensive investigations for various operating and design parameters. Their studies were only focused on the rate of recovered oil quantity disregarding their quality i.e. no data have been reported on the recovered oil efficiency. However, Hammoud and Khalil derived an empirical criterion by applying the principles of dimensional analysis method to correlate the oil recovery rate with the other various parameters, where satisfactory and reasonable agreement was found with their obtainable experimental results. They extended their work to include the effect of the disk material type on the recovered oil quantity [22].

In analogous experimental investigation, however, for a rotating disk in pure oil contained in a closed tank, Christodoulou and Turner [23] indicated that the maximum oil recovery rate can be obtained when the submergence depth of disk in oil is equal to the disk radius and by increasing the speed of rotation. They found also that, for lower submergence depth values, there is an optimum value for the applied rotational speed where after which any further increase of it has nearly no effect on the oil recovery rate. In particular, Turner and his colleges [23-26] suggested improving the performance of the rotating disk skimmer significantly by modifying its shape. They added a cylindrical rim round the disk outer edge, denoted as T-disk skimmer, in an attempt to enhance the oil recovery rate through reducing the oil tail losses.

The problem of vertically rotating disk that is partially immersed in a liquid bath has been theoretically considered by Christodoulou et al. [27], who presented a theoretical model of the oil recovery rate for disk skimmer that rotates at low and moderate speeds. They employed the analysis of the meniscus region by Wilson [28] for the problem of flow control for rotating oil disk skimmers and their study did not extend further into the thin film region on the remainder of the disk. By comparing the results with their previous experimental results, they reported good agreement for large submergence depths. However, for smaller depths, misleading results were experienced. They rendered these findings to the increases in the tail losses which become significant with reducing the submergence depth due to increasing the role of the centrifugal actions that will play. Recently, the same problem was numerically solved by Afanasiev et al. [29], using systematic asymptotic analysis in the limit of small capillary number for very low rotational speed. They derived a dimension-reduced extended lubrication approximation that includes the meniscus region and then solved the resulting nonlinear fourth-order partial differential equation for the oil film profile numerically using a finite element scheme. In general, disk skimmers as most other spill response equipment and materials are greatly affected, often adversely, by weather, represented in ambient temperature, wind, and wave height, and conditions at sea, represented in water currents. A through literature review was recently fulfilled by Fingas [13] to evaluate the performance of disk skimmers under varying weather and conditions at sea. He reported that the disk skimmers performance degrades with increasing wave height and also with relative current. Also, he concluded that, unfortunately, many of the estimations or traditional limits in the literature which varied may not be useful or are completely without basis at all. Ambient temperature has only minimal effect on the disk skimmer performance, where the oil viscosity is mainly influenced by it. However, the severe reduction in ambient temperature to the limit of ice formation represents a large problem during the oil recovery process. In an interesting developing step toward improving disk skimmers performance in moderate wavy sea condition, El-Minshawy [30] successfully tested a modified recovery system model by adding wave's damper in advance to the skimmer to dissipate them prior to reach it.

The aim of the present work is to study experimentally the hydrodynamic performance of the rotating disk skimmer for various design and operating parameters as a primary effort of an integrated research program. This program intended toward developing and improving the performance of disk skimmers. Also, most of the previous investigations were mainly concentrated on the oil recovery rate as the only result to measure the performance of disk skimmers. The present work is paying a great attention to determine the oil recovery efficiency as well as the oil recovery rate to assess the performance both qualitatively and quantitatively. Finally, an optical observation investigation has been carried out to help in interpreting and illustrating the corresponding obtained results from the systematic experimental study.

EXPERIMENAL SETUP AND PROCEDURE

Experimental *Setup*

In order to achieve the pre-mentioned objectives of the present research project, a universal and robust setup was designed, constructed, and then utilized for the desired systematic set of investigations. A detailed schematic diagram and a typical photograph of the experimental test facility, which includes the rotating disk arrangement, containment kit, and control equipment, where its components are shown in Figure 1 and its photography in Figure 2. Five different fabricated rigid disks with varnished plywood sides are individually employed as skimming device in the present study. Three of them have 9 mm in thickness, but, different diameters of 406.4, 355.6, and 304.8 mm. The other two disks have the same diameter of 406.4 mm, but different thickness of 3 and 6 mm. 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 a variable frequency 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 that permits varying the entire system inclination angle with respect to horizontal reference level. This enables studying the effect of disk inclination angle out of vertical plane to the free surface of oil in further future study. 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 spilled oil film thickness above the surface of water to any desired value and controlling the portion of the disk immersed under the surface of the spilled oil. Three types of oil were applied in the present investigation to study the effect of oil properties on the performance of disk skimmers. The typical properties of these oils related to the field of oil spills cleanup are reported in Table 1.

Oil type	**Color**	**Viscosity (mPa.s)**	**Density (kg/m^3)**
Oil1 (hydraulic oil used)	yellow	274.38	882
Oil2 (hydraulic oil used)	black	158.42	876
Oil3 (SAE40 used)	black	524.77	891

Table 1 Typical properties of oils used in the present investigation at 23°C.

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 weighted via a precise digital balance model WH series with a readability of ± 0.5 gram.

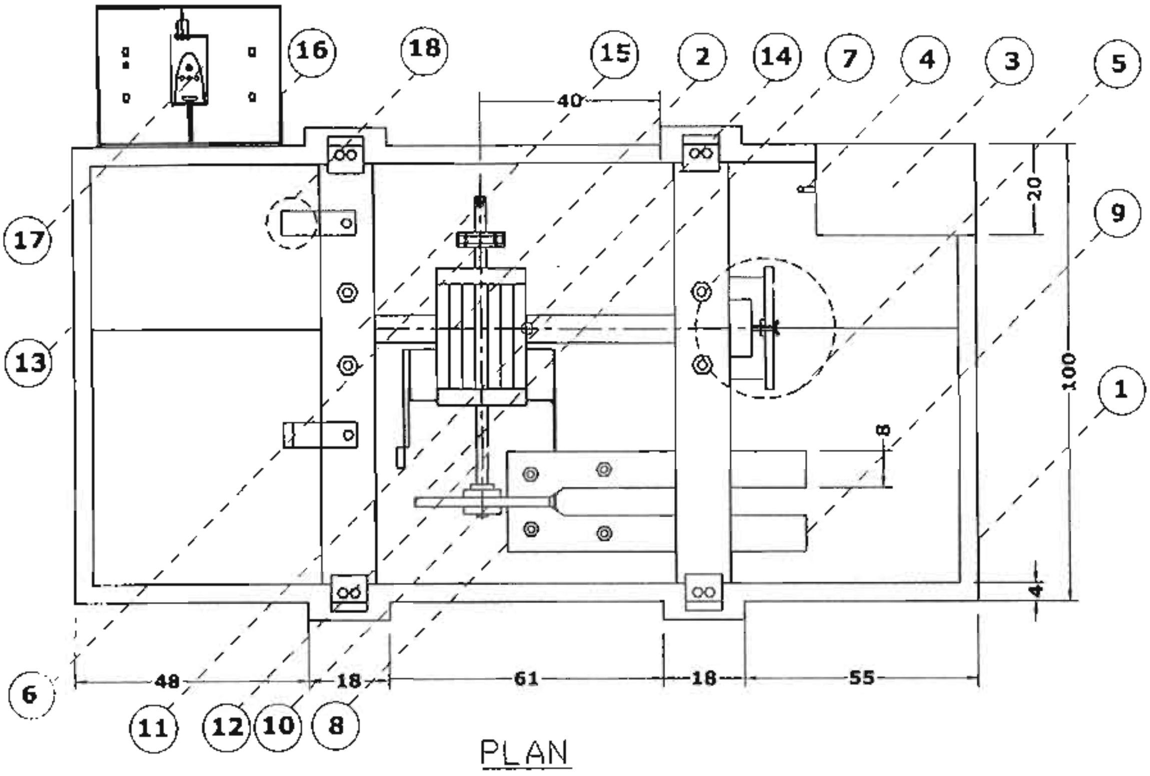

Figure 1: Schematic diagram of the experimental setup.

Part No.	Part Name	Part No.	Part Name	Part No.	Part Name
1	Main reservoir	7	Varnished plywood disk	13	Rigid steel frame
2	Ac electric motor	8	Rubber scrapers	14	Wood partition
3	Compensating oil tank	9	Trays	15	Drain valve
4	Control valve	10	Disk mounting arrangement	16	Mounting beams
5	Disk inclination angle arrangement	11	Mounting rod	17	Control panel
6	Pulley-belt arrangement	12	Rotating shaft	18	Inverter
19	Oil film thickness measuring device	20	Disk holding arm		

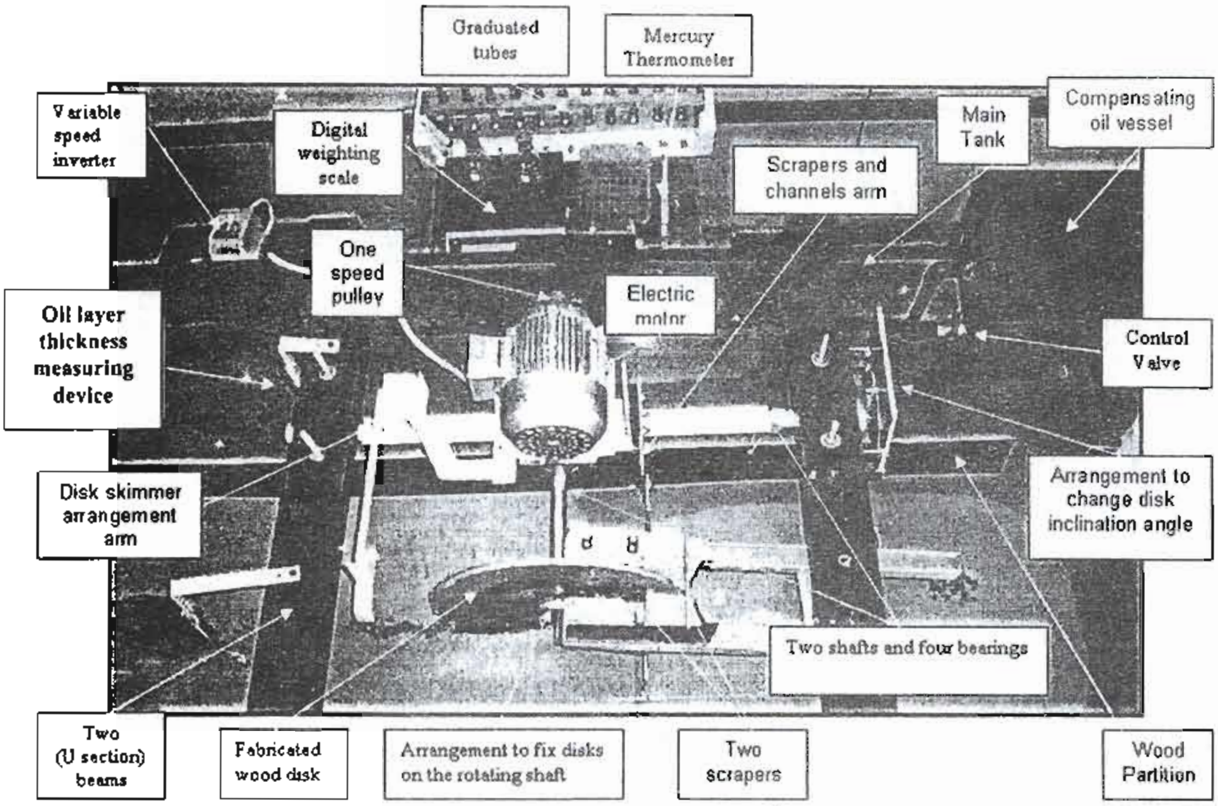

Figure 2: Typical Photograph of the entire experimental setup.

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 from the oil tank (3) on the water surface to the required spilled oil film thickness (10, 20, 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 (14). 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 2 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 oil recovery rate is calculated by dividing the net mass of the recovered oil 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 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 dividing the calculated net oil volume by the collecting oil time.

Where $$ORR = V_{oil} / t$$

Where $$V_{oil} = \frac{\rho_w \cdot V_{total} - m_{total}}{\rho_w - \rho_{oil}}$$

And $$ORE = \frac{\rho_w - \rho_{mix}}{\rho_w - \rho_{oil}}$$

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 22°C and 28°C.

RESULTS AND DISCUSSION

Qualitative Observations

In order to understand the behavior of the spilled oil during its recovery from water, a close visual observation has been provided for some distinct encountered circumstances throughout the skimming process. Thus, Figures 3 and 4 show photographs of the largest disk in operation at various speeds of rotation for the same oil type and spilled oil film thickness of 10 mm for two different values of disk center height above oil-water interface. Obviously, the photographs focused mainly on the near flow field, generated due to disk rotation, of the oil film movement above water at the downstream and adjacent to the disk and on the flow pattern of the adhered oil layer on its uprising dragged out half due to their great importance of influencing the performance significantly and in illustrating the obtained quantitative results.

In general, on one hand, the oil film above water moves orderly in smooth pattern in the meniscus region adjacent to the disk that is bounded with permanent disturbing waves in the near field next to the moving oil pattern, as recognized in Figures 3 and 4. Moreover, these waves separate the moving oil pattern away from the surrounded stationary oil in the reservoir. The close inspections of the abovementioned figures imply that all of these observations look independent of both the disk speed and the disk center height above oil-water interface. However, on the other hand, Figures 3 and 4 provide the constitution of turbulent wake flow in the region downstream to the disk edge intersection with the oil free surface. The length of such wake flow depends inherently upon the disk speed. Also, due to the relatively high viscosity of the oil, the energy in the turbulent wake flow is dissipated and the flow converts soon into smooth orderly flow after some distance in the downstream direction, depending mainly on the disk speed value.

At the lowest applied speed (40 rpm), the adhered oil to the disk draws a well-defined ring on the side disk surface with inner radius equal the disk center height above the oil free surface, as indicated in Figures 3(a) and 4(a). While, a continuous, thick and opaque created layer of the recovered oil appears to separate from the disk along a portion of its edge, commencing from the leaving point of the disk edge out of the oil surface up to the point where the tangent to the disk edge becomes almost vertically, and fall nearly vertically as loss of the recovered oil into the main reservoir again. One can inferred from these observations that the flow pattern throughout the separated oil layer is mainly controlled by the gravity field and negligibly by the centrifugal effects. By further increase of the disk rotational speed (60 rpm), there are no important variations on the shape of the separated layer at disk edge or even its separation position may be registered, as clear in Figures 3(b) and 4(b). Accordingly, these findings imply that in this disk speed range, the amount of recovered oil lost is insignificantly changed. In other words, the oil recovery rate in this speed range continuously increases with speed due to the increase of the disk area rate in contact with the oil.

When the rotational speed is modified to reach higher value (80 rpm), remarkable variations on the shape of the flow field can be obviously distinguished, as recognized in Figures 3(c) and 4(c). The thick and opaque oily layer flow disappears and a new continuous, thin and semi-transparent sheet of water with emulsified oil flow appears. This flow is created as a result of squeezing the oil film asides the dragged out disk sides and splashing the water under the oil film out and circumferentially in the direction of rotation. In fact, the splashed water flow with its relatively high angular momentum gained throughout the rotating disk influences to a great extent the entire flow field at that uprising region of disk. On one hand, it pushes the gravity-falling separated oil flow at disk edge in front of it and confines it at its upper free boundary. It seems as an inclined stationary and suspended dick string-like which tangents the disk edge at one end which travels into new higher position on the disk edge and hits the oil free surface in the reservoir at its other end. Both flows deflect outward at their interface region and slide down to each other to return back into the reservoir by only the gravity effects. On the other hand, the splashed water flow with its high relative velocity operates at the disk edges as a shear layer flow which attracts the other adjacent flows in the nearby with different velocity by the drafting mechanism and imposing them through it. Here, the nearby flows are represented in only the slow dragged out recovered oil flow on the disk surfaces at its edges, which is mainly controlled at such relatively moderate disk rotational speed by the gravity, adhesion, and centrifugal effects. Therefore, the drafted oil flow at the disk edges can be considered as an additional loss of the recovered oil beside the abovementioned separation loss at disk edges.

This aspect can be clearly observed in Figures 3(c) and 4(c), from the curved streamlines appearing like a curved brush across the splashed thin sheet flow.

Instantly, by increasing the rotational speed to get higher value (100 rpm), although similar discussion to that is mentioned above at rotational speed of 80 rpm can be appropriately accomplished here, some new features may be evidently detected. For a moment, the continuous dick string-like as a tangent continues to travel into farther upper location at the disk edge and the surface area of the splashed flow sheet considerably enlarges, as shown in Figures 3(d) and 4(d). Also, large individual droplets of mainly water with a little amount of emulsified oil are separated from the disk surface by the centrifugal action and are flying away in the same plane of disk.

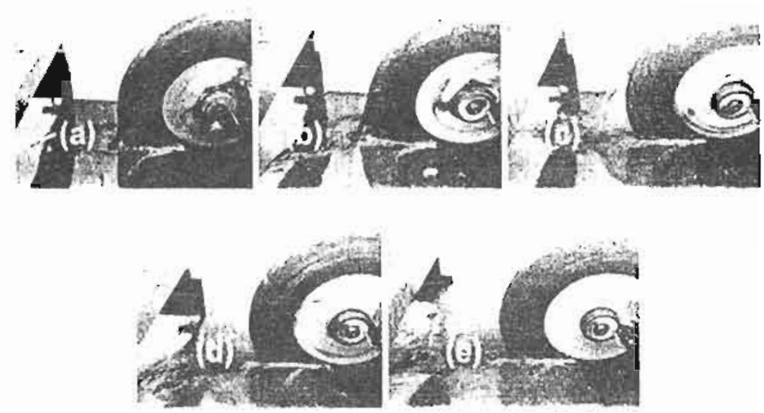

Figure 3: Photographs of disk skimmer of diameter 406.4 mm, for disk center height above oil-water interface of 105 mm, spilled oil film thickness of 10 mm, and Oil3, for different disk rotational speed: (a) N = 40 rpm; (b) N = 60.rpm; (c) N = 80.rpm; (d) N = 100.rpm; (e) N = 120.rpm.

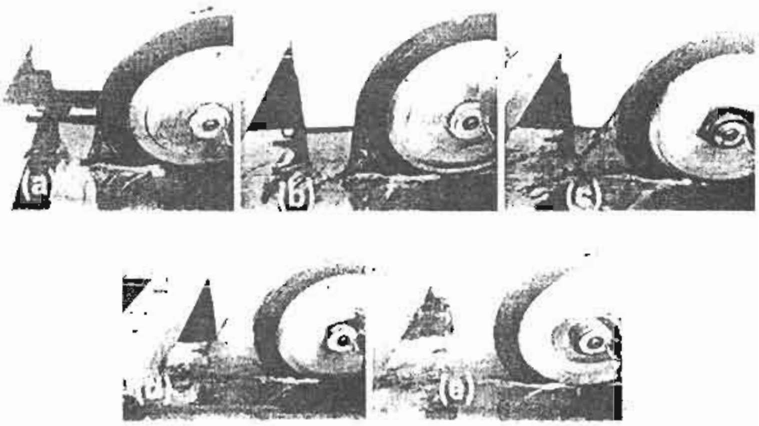

Figure 4: Photographs of disk skimmer of diameter 406.4 mm, for disk center height above oil-water interface of 145 mm, spilled oil film thickness of 10 mm, and Oil3, for different disk rotational speed: (a) N = 40 rpm; (b) N = 60.rpm; (c) N = 80.rpm; (d) N = 100.rpm; (e) N = 120.rpm.

Finally, by increasing the disk speed to the maximum value used in the present study (120 rpm), significant different patterns are clearly identified as recognized in Figures 3(e) and 4(e). The string-like flow ceases to be continuous and to meet the disk edge at specific location as before. It becomes intermittent and random in its nature. However, one can easily distinguish thin splashed sheet with very large surface area and scattered brush-like streak lines throughout the entire field. The intermittent string-like tangent is remarkably advanced to the degree that it becomes meeting the disk edge at its dragged in half, which can be attributed to the enhancement of the centrifugal action in contribution with the other gravity and disk edge angular momentum.

Effect of Design and Operating Parameters

In the following, the influence of disk skimmers performance by the variation of many accompanied design and operating parameters will be individually exhibited and then thoroughly discussed. In particular, the performance of the disk skimmers throughout the entire upcoming results will be expressed in terms of the oil recovery rate (ORR) and the oil recovery efficiency (ORE). Hence, they will be represented as a function of the disk rotational speed for the various studied design and operating parameters.

a – Effect of disk rotational speed and disk diameter

The effect of disk diameter on ORR and ORE for the same disk center height above oil-water interface, spilled oil film thickness, and oil type is shown in Figures 5 and 6 respectively. Obviously, the results depicted in Figure 5 reveal a general dependency of ORR on both the rotational speed and the disk diameter. While for any given studied value of the rotational speed ORR improves continuously with the increase in disk diameter as a result of increasing the oil-strip length (in terms of the meniscus length) in contact with both sides of a stationary disk that leads to increasing the outer oily-wetted ring area when the disk rotates, the case is not always the same with the increase in rotational speed. Where, ORR increases significantly with the rotational speed up to some extent (in the near of 60 rpm). Then, by further increase of the rotational speed, the relationship between ORR and the rotational speed becomes depending upon the disk diameter in some different manner. In some details, while ORR increases slightly or even remains constant for the smallest and middle used disk diameters, respectively, it decays in slow rate for the largest used disk diameter. In fact, the above situations can be explained easily and in connection with the previous visual observations. Clearly, at the beginning, by increasing the rotational speed up to the extent speed value the gain rate of the recovered oil due to the corresponding increase in the rate of the subjected portion of disk area to oil film is increasingly higher than the loss rate of recovered oil due to the separated oil at disk edges. However, by increasing the rotational speed more than the extent value the loss rate of the recovered oil, due to the prescribed mechanisms mentioned before, becomes more significantly important and in counterbalancing with the continuously increased gain rate of recovered oil to produce the net ORR. Finally, the differences among the trends of the three various diameter curves after the extent speed value as shown in Figure 5 can be referred to the expected dependency of the loss rate of the recovered oil with the peripheral velocity at disk edge which of course is proportional to disk diameter. Fortunately, the three selected diameters represent, by accident, the nearly neutral condition and two other cases in around, where the neutral condition is occurred when the increase of both the gain and loss rate of recovered oil are equal.

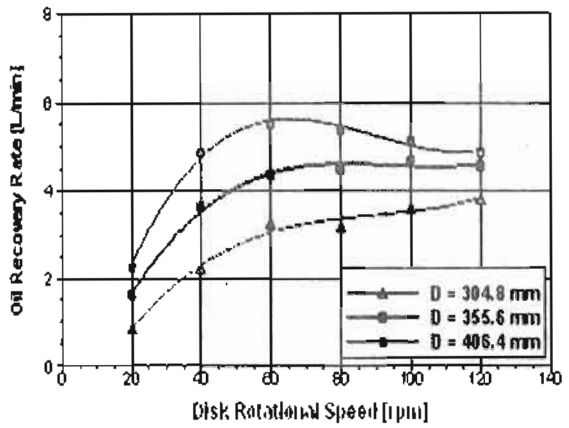

Figure 5: Effect of disk diameter on oil recovery rate for disk center height above oil-water interface of 105 mm, spilled oil film thickness of 10 mm and Oil1.

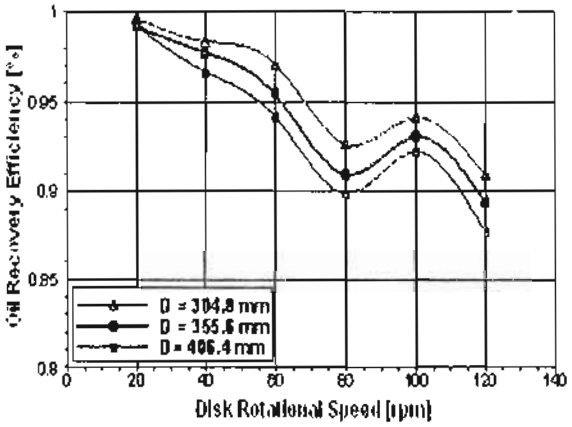

Figure 6: Effect of disk diameter on oil recovery efficiency for disk center height above oil-water interface of 105 mm, spilled oil film thickness of 10 mm and Oil1.

In the same way, the results shown in Figure 6 indicate a general dependency of ORE on both the rotational speed and the disk diameter, however in a different manner. On the contrary of ORR results, ORE is inversely proportional to the disk diameter at any given speed. Logically, this finding can be understood in terms of the immersed area portion of disk surfaces, which is directly proportional to the disk diameter that rotates in water under oil film. By increasing the disk diameter, this immersed area increases and more interrelated water is recovered with oil, which leads to reducing ORE.

In case of the rotational speed, the relationship is not straightforward like the disk diameter. At first, ORE decays at slow rate up to a speed of 60 rpm. After that, it continues to decay, but this time at faster rate up to a speed of 80 rpm. Then, it improves slightly up to a speed of 100 rpm. Finally, it decays again at fast rate up to a speed of 120 rpm. In fact, this associated multifarious ORE approach with the rotational speed is surprisingly found to be similarly repeated throughout the entire of the next obtained ORE results for the other design and operating parameters. This indicates a high degree of confidence in the current experimental results and a unique interpretation for such aspect can be repeatedly introduced.

Again, the obtained results of ORE can be illustrated in connection with the visual observations. In reality, the first speed range in Figure 6 (up to 60 rpm) belongs to the less disturbing region with nearly no squeezing waves or splashed sheet flow appearing in around the disk. Thus, this region is characterized by the lowest degree of mixing between the oil film and the underneath water that is caused by the rotating disk. These reasons result in slow dragging out process of the recovered oil smoothly at the oil-disk meniscus leaving the water away and this leads to the slow rate of ORE within this speed range. By increasing the rotational speed in the second speed range up to 80 rpm the mixing between the oil and the water is augmented due to the appearance of the squeezing waves beside the splashed sheet flow. Hence, more water content in the form of interrelated or emulsified oil with water is expected to drag out. Of course, the mixing process is magnified with speed and this demonstrates the fast decaying rate of ORE with the rotational speed in this speed range. On the contrary to what would be predicted, by further increase of the rotational speed up to 100 rpm, ORE improves slightly by about 2 percent indicating that the water content is decreased, despite increasing the mixing process with speed. As described before, this can be attributed to the flying separated water droplets from the disk surfaces at definite speed value in this range. By more increase of speed the flows patterns become intermittent everywhere due to the high degree of disturbances. Besides the increase of water content due to the high mixing process, some splashed water revolves (Figure 3(e)) with disk to come back on the dragged in portion of disk. As a result, ORE returns back to rapidly decay again.

Finally, by combining the discussion on ORR and ORE results, the following conclusions can be relevantly extracted. Although the disk diameter has a positive effect on ORR, an optimum operated rotational speed (here, in the near of 60 rpm), which is, by way, independent of the disk diameter, should be carefully selected. Also, although the disk diameter has a negative effect on ORE, the operation with the largest used disk diameter near the optimum speed provides ORE value of approximately 94 percent which is still relatively very high and negligibly differs by circa 3 percent less than the corresponding value for the smallest disk. Evidently, these findings validate the superiority of disk skimmers over other means to recover spilled oil from water.

b – Effect of disk center height above oil-water interface

The effect of disk center height above oil-water interface on ORR and ORE for the same disk diameter, spilled oil film thickness, and two different oil types is shown in Figures 7 and 8 respectively. The close recognition of the two figures implies the remarkable importance of such parameter on the disk skimmers performance, which can be summarized in two important points. Firstly, while ORR improves significantly with decreasing the disk center height above oil-water interface, ORE shows very slight dependency on it. In others words, one has to select the disk center height above oil-water interface directly as small as possible without a shred of doubt that ORE will be sensibly affected. Thus, this point suggests that it is desirable to build disk skimmers in practice with disk center just above the oil film free surface. Indeed, the facts stand behind these findings may be rendered to several reasons. In the beginning, similar clarifications to that previously mentioned for the effect of disk diameter on ORR and ORE can be again given here for decreasing the disk center height above oil-water interface. Also, at a given rotational speed, the variations in the horizontal and vertical velocity components profiles and their gradients along the meniscus and interface surface with disk center height above oil-water interface play an essential role for the significant enhancement of ORR and the close difference pattern among the curves of ORE shown in Figures 7 and 8, respectively. Finally, in the time, the gain rate of the recovered oil increases with disk center height above oil-water interface due to the abovementioned reasons as shown earlier in the corresponding photographs, i.e. at the same rotational speed, between Figures 3 and 4, the loss rate of the recovered oil seems to be nearly unaffected. Certainly, this introduces another additional reason for the occurring of augmentation in ORR as clear in Figure 7.

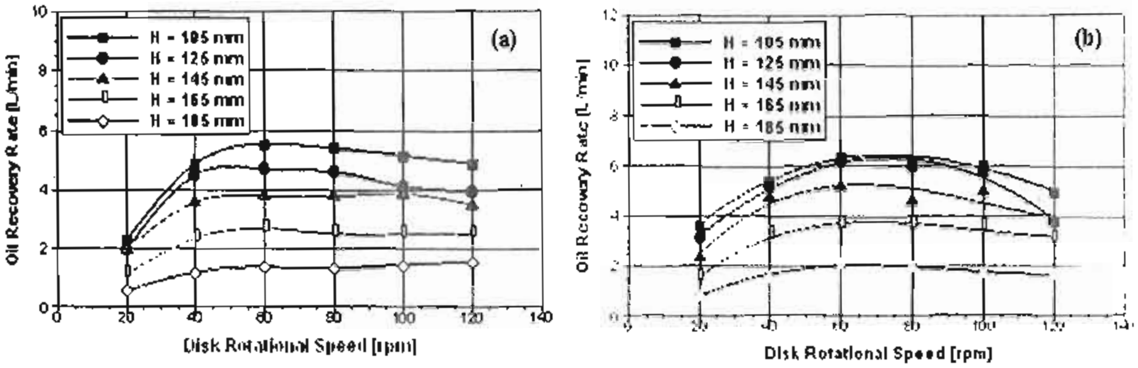

Figure 7: Effect of disk center height above oil-water interface on oil recovery rate for disk diameter of 406.4 mm, spilled oil film thickness of 10 mm, and: (a) Oil1; (b) Oil3.

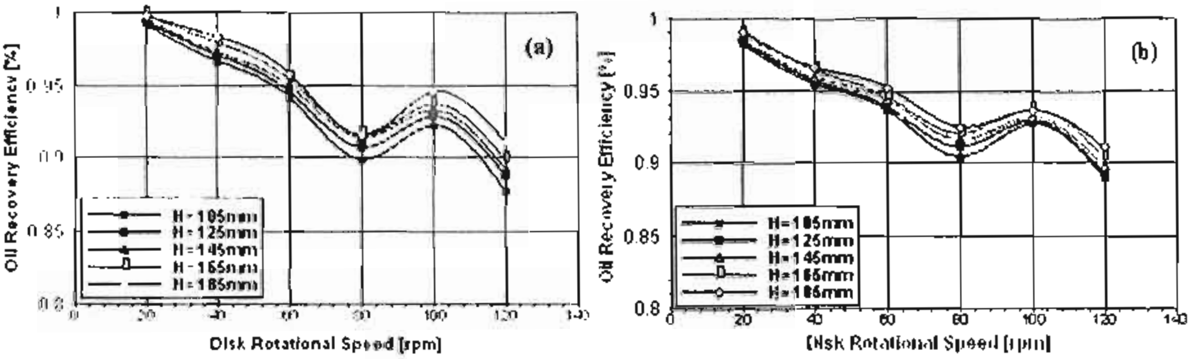

Figure 8: Effect of disk center height above oil-water interface on oil recovery efficiency for disk diameter of 406.4 mm, spilled oil film thickness of 10 mm, and: (a) Oil1; (b) Oil3.

Secondly, despite the large or small differences among the results of ORR or ORE curves, respectively, at the same rotational speed values, the behavior and trends of these curves are nearly repetitively analogous. On one hand, this means that the entire of the subsequent discussion should be restricted to the largest disks that are mounted with disk center height above oil-water interface as small as possible and that operate at the optimum rotational speed. As before, this speed value still remains in the near of 60 rpm and independent of disk diameter and currently of disk center height above oil-water interface, in addition. On the other hand, the same discussion and explanations mentioned formerly about the variation of ORR and ORE with the rotational speed would be repeatedly held here.

c – Effect of disk thickness

The effect of disk thickness on ORR for the same disk diameter, disk center height above oil-water interface, spilled oil film thickness, and oil type is shown in Figures 9. Clearly, the large effects occur in the range of moderate speeds, while at low and high speed values ORR appears to be approximately unaffected. Also, the largest influence takes place at nearly the optimum rotational speed value. Therefore, these findings suggest the use of disks with thickness as thin as possible.

Sensibly, the thicker the disk, the more disturbances at intersection of its edges with oil film free surface and the more losses rate of the recovered oil through increasing the amount of the separated oil and the splashing oil sheet at its edges due to the increase in edges surface area.

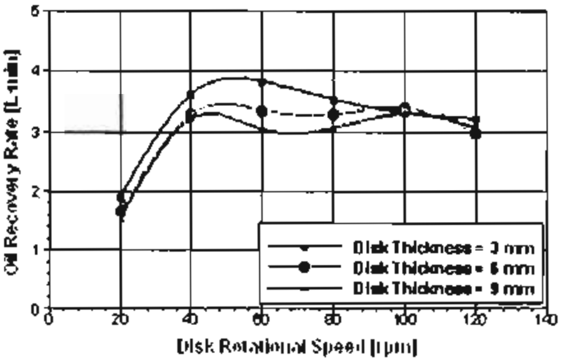

Figure 9: Effect of disk thickness on oil recovery rate for disk diameter of 406.4 mm, disk center height above oil-water interface of 165 mm, spilled oil film thickness of 10 mm and Oil3.

d– Effect of spilled oil film thickness

The effect of spilled oil film thickness on ORR and ORE for the same disk diameter, disk center height above oil-water interface, and two different oil types is shown in Figures 10 and 11 respectively. Evidently, by comparing the behavior of results in the two figures, several important features can be obviously revealed. Firstly, in the time where ORR is enhanced significantly by increasing the spilled oil film thickness, trivial improvement of ORE is entirely displayed. Secondly, the rate, at which ORR is varied with the rotational speed for the thicker oil film, is too much higher than for the thinner oil film. This argument suggests the recommendation of keeping the spilled oil film thickness as thick as possible during the recovery of the oil spills in order tc maximize the performance of disk skimmers. Shortly, this can be accomplished by providing controlled floating booms just shortly after the occurrence of the oil spill and during the recovery process as an integrated system with the disk skimmers. In fact, the reason stands behind these findings can be attributed to the increase of the oil-wetted area on the disk surfaces replacing an equivalent water-wetted area for static disk condition. This causes an elongation of the adhering time scale to keep longer touch periods between the oil and the disk surfaces, and a better permanent substitution to the dragged out oil amount when the disk rotates. Simultaneously, the results of ORE confirm the above discussion throughout the very slight improvement with the spilled oil film thickness wherever they indicate that the velocity field pattern at the meniscus is the predominant parameter influencing the recovery process.

Thirdly, although the same curves trends with the rotational speed are repeatedly noticed, the optimum operating rotational speed, corresponding to the maximum ORR, at the thicker oil film moved to the right to get higher speed value in the near of 80 rpm. However, at such optimum speed value ORE reduces to a figure of nearly 91 percent in a reduction of about 3 percent less than the ORE value obtained before at thinner oil film and corresponding the old optimum speed of about 60 rpm. In reality, a judged argument should be appropriately accomplished here to decide which is more realistic ORR or ORE. Unfortunately, this point is out the scope of the current article.

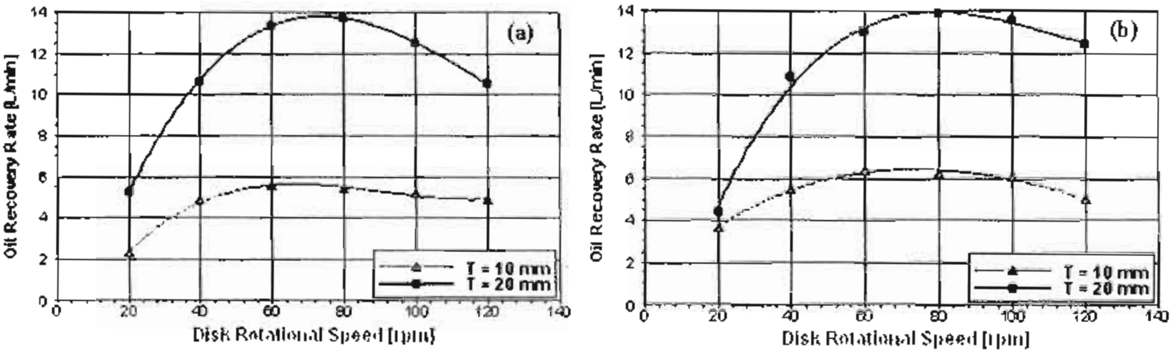

Figure 10: Effect of spilled oil film thickness on oil recovery rate for disk diameter of 406.4 mm, disk center height above oil-water interface of 105 mm, and: (a) Oil1; (b) Oil3.

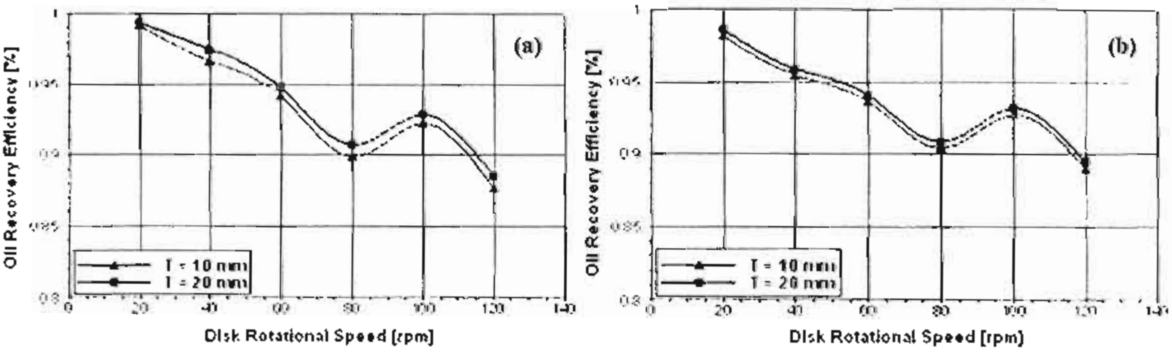

Figure 11: Effect of spilled oil film thickness on oil recovery efficiency for disk diameter of 406.4 mm, disk center height above oil-water interface of 105 mm, and: (a) Oil1; (b) Oil3.

e – Effect of oil type (viscosity)

Finally, the effect of oil type on ORR and ORE for the same disk diameter, disk center height above oil-water interface, and spilled oil film thickness is shown in Figures 12 and 13 respectively. As clear from the two figures although the entire curves behave in general with the rotational speed in the same way described before with the other parameters, the trends this time are found to be slightly different in case of ORR and noticeably distinct in case of ORE. In particular, based on the physical property data given in Table 1, the difference among the three oil types seems almost restricted in the viscosity coefficient. Hence, the peak of ORR appears to take place at slightly higher operating rotational speed, or in other words the optimum operating speed moves a little bit to the right, with viscosity. However, in the near of 60 rpm, also ORR improves reasonably with the viscosity. These results reveal that the higher is the viscosity of the spilled oil, the better is ORR.

Similarly, in case of ORE, two distinct rotational speed zones can be identified. In the first zone, up to nearly 60 rpm, ORE, despite its decaying, improves in very narrow pattern with decreasing the viscosity. While in the second zone at higher speeds, ORE reverses to be improved with the viscosity and deteriorated, instead, for the oil with the lowest viscosity value. These findings seem to be acceptable in terms of elongating the adhering time scale and decreasing the velocity of the flow fields everywhere with viscosity. As a result, the opportunity of the recovered oil to grow thicker on the disk surfaces is better and in contrast to separate at the dragged out edges is lower at the same speed with increasing the viscosity, thus, improving ORR. Also, reaching high level of disturbances at the meniscus and building in the splashed sheet behind the disk is achieved slower, i.e. at higher rotational speed, with lowering the viscosity. This causes moving the position of the optimum rotational speed value to the right with viscosity. However, with respect to the decreasing of ORE with viscosity at lower rotational speeds is due to increasing the water contents in the thicker recovered oil layer in relative with the thinner one. At higher rotational speed values, the level of disturbances becomes higher and the shear stress required to squeeze the oil free surface away from the disk at the meniscus becomes smaller with decreasing the viscosity. This leads to promote the ability of the oil film layer to become intermittent earlier that causes increasing the interrelated water content and thus, decreasing ORE.

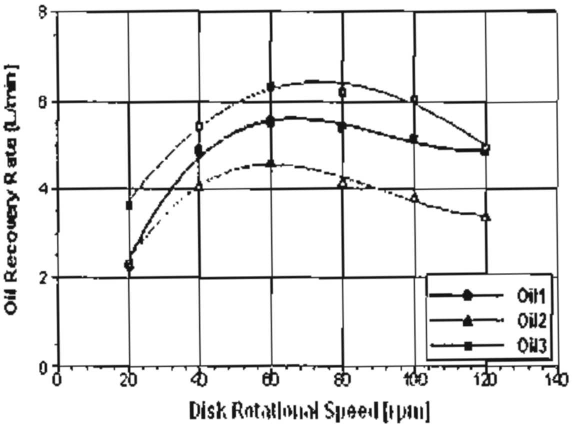

Figure 12: Effect of oil viscosity on oil recovery rate for disk diameter of 406.4 mm, disk center height above oil-water interface of 105 mm, and spilled oil film thickness of 10 mm.

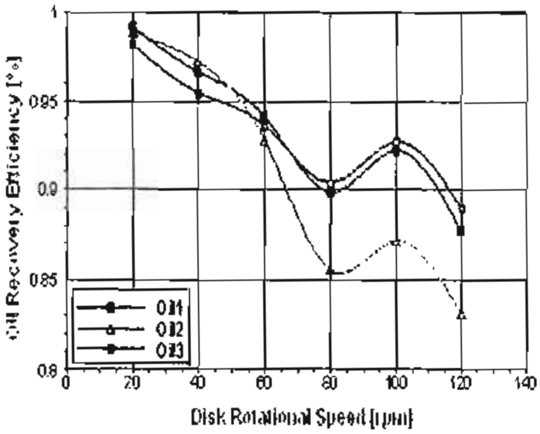

Figure 13: Effect of oil viscosity on oil recovery efficiency for disk diameter of 406.4 mm, disk center height above oil-water interface of 105 mm and spilled oil film thickness of 10 mm.

CONCLUSIONS

Throughout the present work, arguments with the help of visual observations are conducted to provide detailed understanding for broad events during applying disk skimmers for the oil recovery process. The main findings that can be extracted from this investigation can be summarized as follows:

☐ The optimum operating rotational speed of disk skimmers should be carefully selected and then adjusted on the base of maximizing ORR. This value was found to be dependent on the spilled oil film thickness.

☐ The use of thin and large diameter disks at the optimum operating rotational speed is preferable to improve ORR considerably.

☐ Because the decrease in the disk center height above oil-water interface revealed remarkable augmentation in ORR and nearly unimportant influence in ORE, thus, it is desirable to build disk skimmers in practice with disk center just above the oil film free surface.

☐ ORR was found to be significantly enhanced with spilled oil film thickness. Hence, keeping thick oil film during the recovery process is important and critical for optimizing the performance. Indeed, this can be practically achieved by employing floating booms just the occurrence of the spill and during the oil recovery process.

☐ Despite the validity of disk skimmers for the recovery of wide range of oils with different viscosity values, they showed better performance with higher viscous oils.

☐ Generally, the flows conditions at the dragged out edges of disk skimmers are the key feature of optimizing their performance to a great extent. Therefore, particular care should be devoted toward understanding these flows patterns at these regions and then their controlling.

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