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◉ 論　文

Investigation on the Recovery Rate of Adhesion-Type Oil Skimmers

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(96년 12월 26일 접수)

흡착식 유회수기의 회수율 추정에 관한 연구

김 장 환* · 현 범 수**

Key Words : Adhesion-type(흡착식), Oil Skimmer(유회수기), Withdrawal Rate(회수율), Stability(안정성), Film Thickness(유막두께), High Reynolds Number(고레이놀즈수), Optimal Speed(최적속도)

초 록

흡착식 유회수기의 운전조건을 결정하는데 있어서 스키머의 구동속도와 기름의 물리 · 화학적 성질에 따른 스키머의 유회수율을 예측하는 것이 필요하다. 이 문제에 대한 이론적인 접근으로 수직구동 평판상에 부착된 기름층의 자유표면유동을 두가지 방법으로 조사하였다. 그 하나는 표면코팅시 얇은 유막에 대하여 수행하는 정상유동해석이며, 다른 방법으로는 스키머 표면유막에 대한 안정성해석이다. 해석은 기름층이 충분히 두꺼워서 스키머는 기름층에서만 작동한다고 가정하였다. 이론추정 결과는 롤러타입의 스키머에 대하여 계측한 실험치와 비교하였는데, 유막의 안정성해석 결과가 유회수기와 같이 상대적으로 고레이놀즈수에서 작동하는 유동의 경우에는 정상해석보다 좀 더 합리적으로 유막의 두께를 산정함을 알 수 있었다. 한편, 물위에 떠있는 얇은 유막층의 유회수성능도 실험하여서 주어진 유막두께에 대하여 롤러의 최적구동속도를 함께 조사하였다.

1. INTRODUCTION

Oil enters the marine environment by a number of different routes as a result of both human activities and natural processes, causing serious impact on coastal activities and marine life. The most common way of response to marine oil-spill is to use oil barriers to prevent the spread of oil and to concentrate it into a thick layer so that it can be recovered using skimmers. Among various kinds of mechanical oil recovery equipments, we here consider the adhesion-type oil skimmer, utilizing the adhering property of highly viscous oil on solid surface.

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The performance of adhesion-type skimmer in ocean depends on environmental conditions as well as skimming processes like oil-slick thickness, its physical properties, and the shape and operating speed of skimmer. As a first step of the study in this field, theoretical analysis was made for a vertically-driven plate operating in a pool of sufficiently deep oil layer. We borrowed some ideas from the analyses commonly made in coating industry where the recovery rate is mainly governed by capillary number and the effect of Reynolds number is neglected. Since the operating condition of oil skimmer is relatively high in speed compared to the coating flow, its inertial effects was taken into account indirectly by carrying out a stability analysis for the oil film on solid surface to complement their results.

In experimental phase, a roller-type skimming device was made and tested to verify the results of theoretical analysis. Another purpose of experiments was to simulate the more realistic situation of spilt oil on sea for which thin oil layer was added on the water pool. Although theoretical analysis for such a two-layer fluid has not been made yet, it should be made in a near future.

It was found from the scope of present investigation that there exist some limitations of maximum film thickness and speed for effective oil recovery. Practically, stability analysis was useful in some sense to determine the criterion of oil recovery system in a conservative way.

2. THEORETICAL ANALYSIS

2.1 Steady Analysis

Although many investigators have studied on the recovery of adhesion-type skimmers by experiments, the theoretical analysis on this topic is rarely found. The theoretical approaches on a similar problem can, however, be easily found in the field of coating industry. Indeed the basic mechanism of dip coating, driving out surfaces immersed in a coating liquid, is identical to that of the oil recovery by adhesion type oil skimmers. As a theoretical analysis of this problem the formation of a liquid film on a vertically driven flat plate has been treated by many authors, naming a few, Landau & Levich$^{5)}$, White & Tallmadge$^{10)}$ and Spiers et al$^{8)}$. A thorough review on this topic can be found in Ruschak$^{7)}$. Their analyses have been made under the assumptions that the Reynolds number and the capillary number, which are defined as

$$Rn = \frac{Uh}{\nu}, \quad Ca = \frac{\mu U}{\sigma} \qquad (1)$$

are small, where μ, ν, σ denote the dynamic viscosity, the kinematic viscosity and the surface tension of the liquid, respectively. The oil film on the plate was also assumed to be stable and in a steady state with all inertial effects neglected. In the steady analysis, the liquid region is divided into three parts as shown in Fig. 1. The characteristics of the flow in each region can be summarized as follows

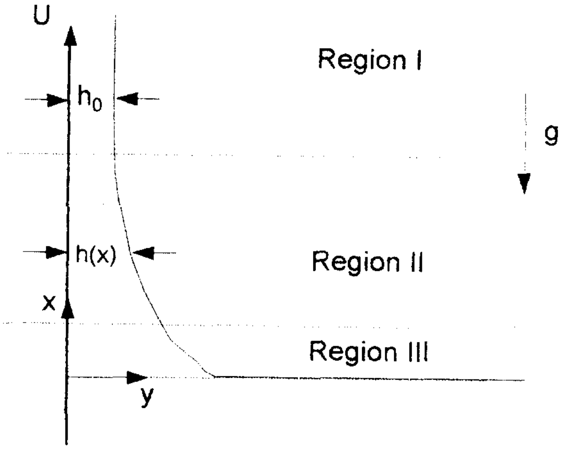


Fig. 1 Profile of a liquid film adhering to a vertically driven surface

Region Ⅰ : The thickness of the liquid film h(x) has a constant value h_0. The flow is one dimensional and governed by viscosity and gravity.

Region Ⅱ : The thickness is a function of x. Viscosity, gravity and surface tension should be considered all together in this region.

Region Ⅲ : The flow field is nearly stagnant. Gravity and surface tension are considered.

The flow field in the region I and III can be obtained exactly due to the simplicity of the flow field. Among them, the result in region I provides us the relation between the film thickness and the velocity profile,

$$u(y) = U - \frac{gh_0^2}{2\nu}\left\{\left(\frac{y}{h_0}\right)^2 - 2\left(\frac{y}{h_0}\right)\right\} \tag{2}$$

and the flux of the liquid

$$q = Uh_0\left(1 - \frac{\rho g h_0^2}{3\mu U}\right) \tag{3}$$

If we define dimensionless thickness T_0 and flux Q as

$$h_0 = T_0(\nu/g)^{\frac{1}{2}} U^{\frac{1}{2}}, \quad q = Q(\nu/g)^{\frac{1}{2}} U^{\frac{3}{2}} \tag{4}$$

the relation between them can be obtained from eq.(3) as

$$Q = T_0\left(1 - \frac{T_0^2}{3}\right) \tag{5}$$

The flux of the liquid film shows its maximum value at T_0 = 1 and $Q = \frac{2}{3}$, even though the actual value of T_0 depends on the Reynolds and the capillary numbers. To determine T_0 the analysis of the Region II is necessary. Approximate analyses have been made with more or less restrictive assumptions on the flow field. The results of steady analyses of some authors are shown in Fig. 2, compared with Spiers' experimental results. The details of the theoretical analyses can be found in Spiers et al[8]. We can find that the experimental values of T_0 agree well with the theoretical values when *Ca* is less than unity, but approaches to a constant value about 0.8, which could not be predicted in the theoretical results.

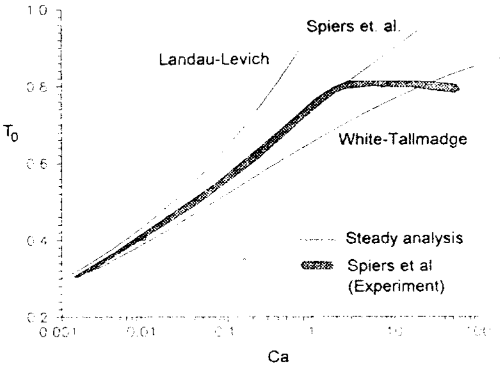


Fig. 2 Comparison of steady results with experiments

2.2 Stability Analysis

As mentioned previously the steady analysis given above was made under the assumption that the driving speed and the thickness of liquid film are very small. While these assumptions are quite suitable for the coating process, the analysis of the liquid film in higher driving speed is required to determine the optimal operating condition of oil-skimming process. The role of inertial force, which is neglected in the previous analyses, become important in this case. As a simple way to consider the effect of inertial force, we propose the stability analysis for the one-dimensional flow in Region I. In our knowledge, the stability analysis of the flow on a vertically driven plate has not been reported yet.

The parallel flow in the Region I of Fig.1 can be transformed to the free-falling problem on a stationary plate by a simple translation in the direction of the driven velocity U. That is, if we denote the velocity profile on a driven plate and a stationary plate as u_d and u_f, respectively, the relation between them can be given as

$$u_d = U + u_f \tag{6}$$

The free-falling problem has been applied to heat transfer due to liquid film formed on heat condensers[1)~3)]. Since the contexts of the stability analysis is rich in this field we adopted the result from them. To interpret the result of the free falling problem to the driven problem, we use the concept of absolute instability. That is, the driven speed for a given thickness of the film should be faster than the maximum group velocity of the unstable waves in free-falling liquid film. The maximum thickness T_0 on the driven plate and the maximum group velocity $(C_g)_{\max}$ on a stationary plate can be related each other by the following equation[4)]

$$T_0 < \sqrt{\frac{3}{(C_g)_{\max}}} \tag{7}$$

where the group velocity is non-dimensionalized by the mean velocity of the steady profile. The maximum group velocity can be obtained by either the linear stability analysis or the direct simulation of the wave propagation on the liquid film. In the latter case the nonlinearity of propagating wave is taken into account, thus more realistic criterion on the maximum possible film thickness can be obtained.

As a linear stability analysis we adopt the long wave approximation of Alekseenko et al[1)]. Following the procedure described in Kim & Hyun[4)], we can obtain the following results.

$$T_0 = \sqrt{0.643 - \frac{0.934}{C_a R_n^3} + O\left(\frac{1}{C_a^2 R_n^6}\right)} \tag{8}$$

The film thickness depends on Ca and Rn and approaches to a limit

$$T_0 \rightarrow 0.802 \quad as \quad C_a R_n^3 \rightarrow \infty \tag{9}$$

For the nonlinear stability analysis we simulated the solitary waves on film thickness numerically. The Navier-Stokes equation is discretized by a finite element method with second order polynomial interpolation of the velocity profile. By monitoring the evolution of nonlinear waves due to initial disturbance, the maximum group velocity was obtained from solitary waves and found to depend both on the Reynolds number and the capillary number. The speed of the solitary wave was increased with increasing Reynolds number. Since the purpose of the stability analysis is to complement the steady analysis at high Reynolds number, we concentrated our attention only on the maximum speed of the solitary wave treated in the numerical simulation. The numerical solution could be obtained up to Rn = 10, for which the computed profile of solitary wave is shown in Fig.3 as a critical case.

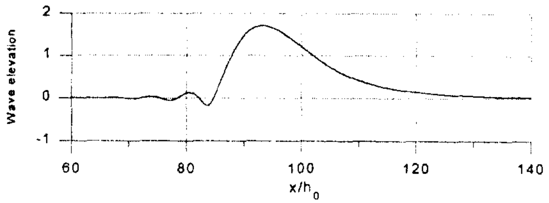


Fig. 3 Computed profile of solitary wave on a vertically driven plate.

With higher values of Rn, no bounded numerical solution was attainable, meaning a propagation speed at Rn = 10 is the speed limit of group velocity which was 8.25 from the calculation. The corresponding maximum allowable thickness was calculated to be T_0 = 0.60 according to eq. (7).

As a summary of the stability analysis, the stability criterion at relatively high Reynolds number and/or capillary number could be given as follows.

Linear stability analysis:

$$T_0 < 0.80, \ Q < 0.63 \ \text{for} \ R_n C_a^2 \gg 1 \qquad (10)$$

Nonlinear stability analysis:

$$T_0 < 0.60, \ Q < 0.53 \ \text{for} \ R_n \gg 1 \qquad (11)$$

In Fig.4 the results are compared with the previous steady analyses and their experimental results. The result of linear stability analysis shows a good agreement with the experimental results when C_a is greater than 1 where the previous steady analyses loose their validity. The lower estimation of the nonlinear theory can be explained by the fact that the experiments in the coating flow are performed in the low Reynolds number region. Further discussion will be made later with our experimental results.

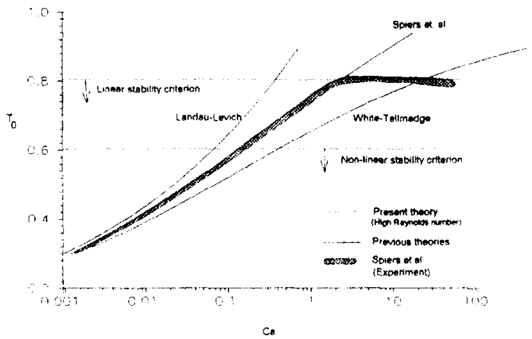


Fig. 4 Comparison of theoretical results with previous experiments

3. EXPERIMENTAL APPARATUS AND PROCEDURES

Sketch of experimental apparatus is given in Fig. 5. The equipment consists of liquid bath and a 14cm diameter PVC roller of 50cm wide. According to Ueda et al.[9], the property of roller material gives little effect on withdrawal rate. The size of bath and the liquid depth were sufficiently large to minimize their effects on the liquid film. A roller, whose speed reaches up to 5 revolution per second, was driven by a variable speed electric motor. To ensure the liquid depth in bath constant, the amount of fluid corresponding to the withdrawal rate by a roller was steadily supplied to the bath from reservoir using a submergible pump. Sampling time was measured using contact switches active only when the desired quantity of withdrawn fluid is reached, thus obtained time and fluid quantities.

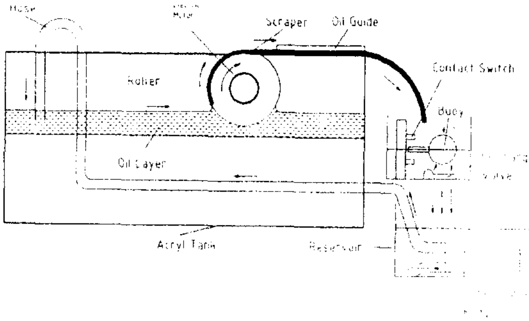


Fig. 5 Sketch of experimental apparatus of roller skimmer

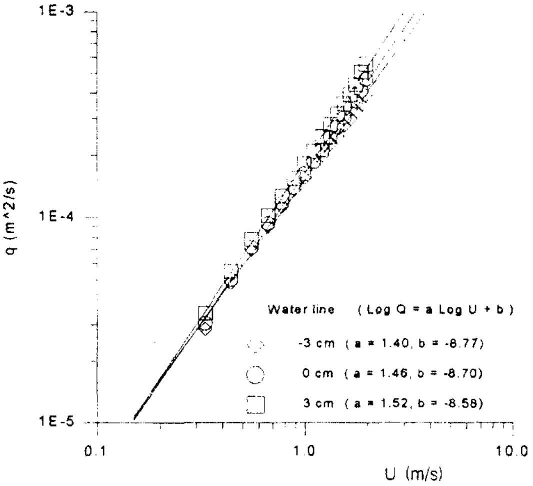
Two fluids were used in the study: tap water with its viscosity of 1 centiStoke and soybean oil of 70 centiStokes at 20°C.

4. EXPERIMENTAL RESULTS

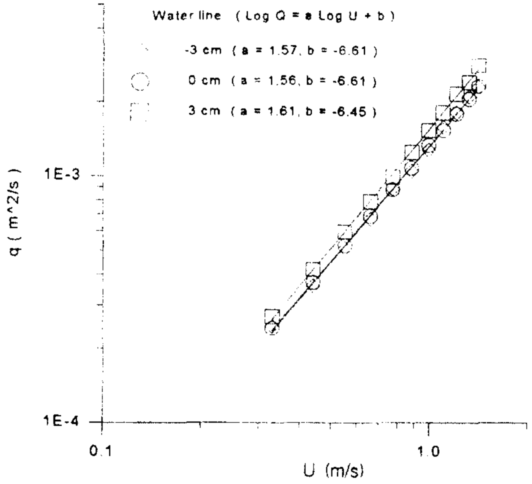
4.1 For Single Fluid

Fig. 6(a) shows the withdrawal rate against roller speed for water, where the effect of fluid depth (fluid level 3cm above the roller axis, on roller axis, 3cm below roller axis) is also presented. While withdrawal rate is slightly increased with increasing fluid level, its effect appears to be small. For soybean oil in Fig. 6(b), withdrawal rate is increased by one order of magnitude compared to that for water, proportional to the square root of kinematic viscosity.

Measured data for all measured conditions were fitted into a single curve by scaling of the viscous effect as seen in Fig. 7. Also shown in this figure are data for A-Oil (μ=10 cst) and B-Oil (μ=250 cst) by Ueda et al[9].



(a) Water



(b) Soybean Oil

Fig.6 Withdrawal rate of Fluids by a roller

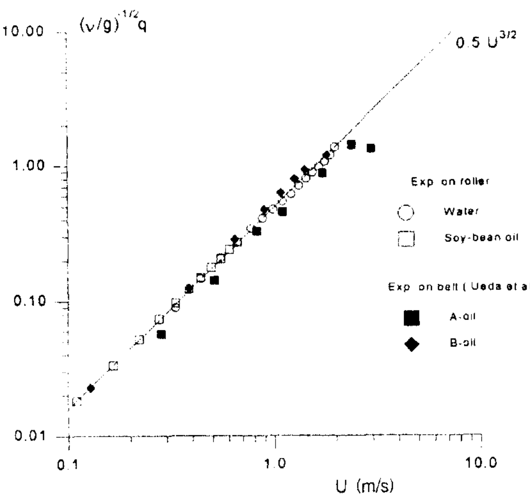


Fig. 7 Withdrawal rate of various liquids by roller and belt.

The same values are plotted in Fig.8 using dimensionless quantities of *Rn* and Q defined in eq.(1) and (4), respectively. In this figure the experimental results are compared with the maximum flow rate predicted by stability analyses. It can be found that the nonlinear analysis provides a reasonable bounds of withdrawal rate at high Reynolds number.

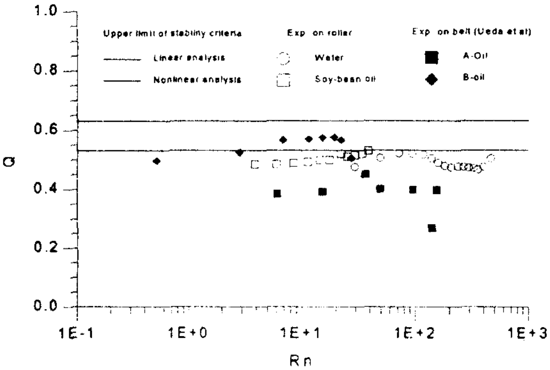


Fig. 8 Nondimensional withdrawal rate against Reynolds number.

Fig. 9 shows nondimensional thickness plotted against capillary number. Lines of T_o=0.8 and 0.6

represent the stability limitation of film thickness obtained from the linear and the nonlinear stability analyses, respectively. All the data including the present data as well as Ueda's are fallen below $T_0 = 0.8$, showing a totally different trend with Spiers et al[8]. Even though plotted data were obtained rather incautiously in surface tension, it is likely that major reason lie on the effect of Reynolds number. Practically, the consideration of Reynolds number would be more important than capillary number in marine oil-spill recovery system due to its operating speed. By the way, stability limitation could be useful in some sense to determine the criterion of oil recovery system in conservative way.

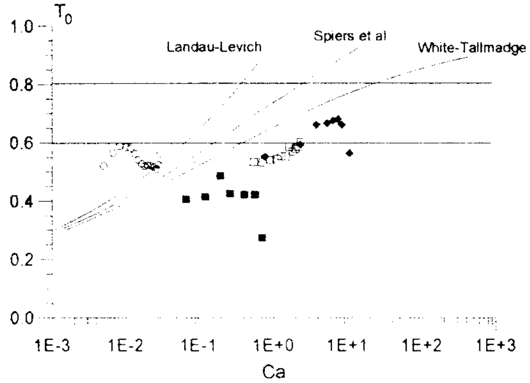


Fig. 9 Nondimensional thickness versus capillary number. See Fig.8 for more information.

4.2 Oil Layer Over Water Pool

To simulate the real situation of spilt oil on sea, soybean oil layer whose thickness was varied from 0.5cm to 2cm was added on the water pool.

As seen in Fig. 10, the recovery rate decreases when the thickness of oil layer decreases. The slope of recovery rate is reduced for oil layer thickness less than 1cm when roller speed is increased. This result showed a similar tendency with Ueda[9]'s results given in Fig. 11 where the recovery rate is almost constant for U > 0.5m/s, meaning that oil withdrawal is effective at roller speed higher than 0.5 m/s. It was observed by eye that this trend seems to be due to the reduction of oil thickness very near a roller, even though the thickness of oil layer over entire basin was maintained to be the same. It implies that there exists the thickness limitation for effective oil recovery, which appears to be at least 0.5cm in slick thickness. Finally, it should be noted that the separation of water content from withdrawn fluid was not necessary since water amount appeared to be negligible in the present experiments.

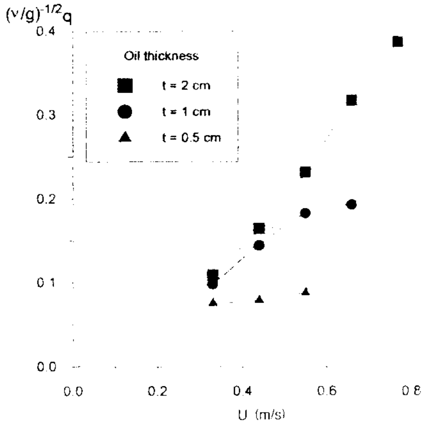


Fig. 10 Withdrawal rate of soybean oil by roller skimmer

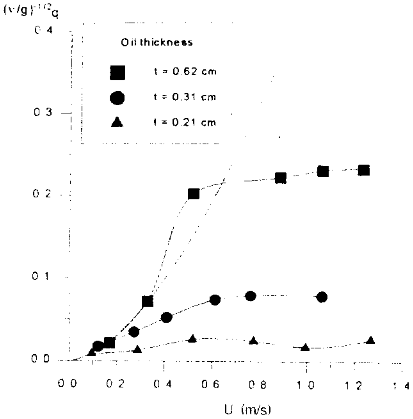


Fig. 11 Withdrawal rate of A-oil by belt skimmer (Ueda et al[9])

5. CONCLUSIONS

Theoretical estimation of the withrawal rate of adhesion-type oil skimmer was made by the stability analysis of liquid film on a vertically driven surface. Comparing with the previous studies made in the field of coating industry, it was found that the stability analysis can be used as a complementary estimation of the film thickness at relatively high driven speed where the previous theoretical result looses its validity.

Measurements were made to obtain the recovery rate of the roller-type skimmer, where the measured withrawal rate fall below the stability criterion. It proved the present analysis to be a better estimate than that in coating problem. This is presumably due to the fact that the range of Reynolds number for the skimming process is relatively higher than for the coating process, which meets the basic assumptions used in stability analysis.

Oil layer was added on water pool to simulate the effect of slick thickness floated on sea in effectiveness of oil recovery. When the slick thickness is less than 1cm the recovery rate ceases to increase at driving speed higher that 50cm/s. For oil slick thicker than 2cm, the recovery rate was practically identical to that of the single fluid case in the range of the operating speed of the present experiment.

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◉ 論　文

벨트식 유회수기를 사용한 디젤유 회수에 관한 실험적 연구

송동엽*·윤경환**

(97년 4월 14일 접수)

An Experimental Study on the Recovery of Diesel Oil Using a Belt Type Skimmer

Dong-Eub Song* · Kyung-Hwan Yoon**

Key Words : Skimmer(유회수기), Belt Type Skimmer(벨트식 유회수기), Oil Spill(누유), Oil Recovery(누유 회수)

Abstract

Removal of spilled oil over the sea and the river has become one of the urgent problems in these days. Removing oil using mechanical devices are recommended because chemical dispersion can cause the secondary contamination in the environment.

In the present study a series of experiments were carried out to study the effect of working conditions of a belt type skimmer on the rate of recovery for the spilled oil. The oil chosen for the present experiment was diesel oil. Three different situations, namely, upward, downward, up-and-downward pickup have been investigated for various contact angles, belt speeds and oil thicknesses.

The results show that the rate of oil recovery for the case of downward pickup with a contact angle of 45° shows the highest among all the conditions. For the removal of spilled diesel oil the optimal belt speed can be found as the critical value to reach the saturated pickup rate for a given oil thickness. The recovery rate of bunker C oil shows 4～6 times higher than that for diesel oil. And the optimal belt speed for bunker C oil can be found less than that for diesel oil for the same slick thickness.

1. 서론

하천이나 해상에서의 누유에 의한 환경오염은 유류사용의 증가와 더불어 더욱 심각한 문제로 대두되고 있으며 현재 생산되고 있는 원유의 약 0.17%가 하천 또는 해상에 누유되고 있는 것으로 알려지고 있다[1]. 한편, 이와 같은 누유에 의한 해상오염은 점차 대형화되고 있고 빈도수 또한 증가

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