



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Ocean Engineering 31 (2004) 943–956

OCEAN
ENGINEERING

www.elsevier.com/locate/oceaneng

Fate of dispersed marine fuel oil in sediment under pre-spill application strategy

Jian Hua *

Department of Marine Engineering, National Taiwan Ocean University, Keelung 202, Taiwan, ROC

Received 5 August 2003; accepted 3 December 2003

Abstract

A comparison of the movement of dispersed oil in marine sediment under two dispersant application scenarios, applied prior to and after oil being spilled overboard, was examined. The pre-spill application scenario caused much less oil to be retained in the top sediment than post-spill scenario. The difference in oil retention in the top sediment between pre- and post-spill application scenario increased with increase in fuel oil temperature. For fuel oil above 40 °C, the difference in the effect of pre-spill application strategy under various water temperatures was negligible. When soap water was used as replacement for chemical dispersant, almost one-half as much oil was retained in the top sediment as that when using chemical dispersant. The adsorption of dispersed oil to the top sediment was almost proportionally decreased with doubling of soap dosage.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Dispersed oil; Sediment; Oil spill; Dispersant; Adsorption characteristic; Oil dispersion

1. Introduction

The extensive carrying of crude oil and its products over oceans has increased concerns about the effects of accidental spillage of petroleum hydrocarbons in the marine environment. Most studies concerning oil spill remediation aim at crude oil carried by tankers. However, tankers are far more restrictively regulated nowadays in design and construction and in operation practice. The requirement of double-hull design and the tank washing and loading–unloading procedures has effectively limited the possibility of spill from tankers. It is thus reasonable that fuel oil spill

* Tel.: +886-2-24622192x7106; fax: +886-2-24633765.

E-mail address: huajian@mail.ntou.edu.tw (J. Hua).

from nontankers, especially over-sized cargo ships which are commonly loaded with more than 1000 tons of fuel oil, has become a major issue as far as marine oil pollution is concerned. For instance, the Greek bulk carrier, M.V. Amorgos, ran aground on January 14, 2001, in south Taiwan, causing some 1150 tons of fuel oil to leak out and contaminate the pristine coastline that constitutes part of Kenting National Park, generating enormous public concern.

Major marine oil spills highlight the need for cost-effective and environmentally responsible mitigation technologies. Experience from many similar oil spill incidents worldwide indicates that the “first-minute response” principle plays a key role as an environmentally safe and cost-effective response to marine oil spills, particularly when they take place near shore. However, it is generally recognized as a real problem to carry out effective response immediately from land after an incident, as bad weather conditions usually accompany an incident, limiting the capability of response in most cases. This study, therefore, proposes an immediate response right on board of ship facing possible oil spill, instead. First-minute actions can be taken on board ship to pre-treat oil with dispersant in the storage tank, as part of the emergency response procedure prior to evacuating the damaged ship. In practice, engineers of ships are almost unexceptionally well trained to respond to various emergency situations such as grounding and collision, and drills are carried out periodically. Such an immediate procedure may facilitate more effective follow-up environmental remediation than action taken after oil has already spilled into the sea.

Since the early days of contingency planning for marine oil spills, chemical dispersants have been widely used to combat oil spills at sea. However, after the incident of the Torrey Canyon oil spill in 1967, concern has been aroused that the use of dispersants might be of questionable value and should not be recommended. Nevertheless, dispersants still play an important role in oil spill contingency planning in many countries, leading to continuous research into the effectiveness, limitations, and application techniques of dispersants.

The use of dispersant in comparatively shallow coastal water might move more oil into marine sediments than would be the case with oil left to disperse naturally, or it might make the oil more mobile, causing it to move offshore and be diluted in deeper water. The interaction of dispersant with oil is only partially understood. An earlier study has proposed factors influencing effectiveness of dispersion include oil viscosity, dispersant drop size, water temperature, and oil/water partitioning characteristics of the dispersant (Mackay et al., 1984). A general relationship between effectiveness F (expressed as fraction of oil dispersed) and other parameters was postulated by Mackay et al. (1984) as

$$F = 1 - \exp(-K_E K_O K_D R),$$

where K_E is a constant determined by the turbulence conditions, K_O is a constant determined by the oil, especially its viscosity, K_D is a constant determined by the dispersant, and R is an effective dispersant to oil ratio.

Because the primary fate of spilled oil may be sedimentation, it is important to know whether chemical dispersal increases or decreases transport of hydrocarbons

to the sediment. Few studies have been conducted to determine the fate of dispersed oil in sediments and the factors controlling the interactions of dispersed oil with marine sediments and the potential effects on benthic biota.

Existing data from earlier studies pointed to different sorbent properties as keys to sorption in given situations (Pionke and Chester, 1973; Bailey and White, 1970). However, owing to the high degree of variability and complexity in sediment composition and potential sorptive interactions, there was relatively little understanding about the sorption of oil hydrocarbons to particles in the marine environment. The agglomeration of both sediment particles and oil droplets was investigated (Harris and Wells, 1979; Mackay et al., 1982; Little et al., 1986). The results suggested that chemical dispersion of oil led to reduced interaction with suspended particulate matter or sedimentation.

In a more recent study on oiled sediments collected from Prince William Sound, Alaska, Bragg and Yang (1999) observed a process that involved the creation, in seawater, of a stable emulsion of micron-sized droplets of oil surrounded by micron-sized clay. The process of clay–oil flocculation reduced the adhesion of oil to other materials, such as sediment or bedrock, and, once formed, the clay–oil flocs were easily removed by even gentle water motion (Owens, 1999).

Previous research concerning the effectiveness of dispersant and the behavior of dispersed oil in marine environment including in marine sediment assumed without exception that measures used to respond to oil spills have been taken after oil was discharged overboard. Therefore, research concerning techniques such as chemical and bioremediation treatment were based upon the assumption that it was applied following oil being spilled into the water body, and for most cases, the shore was tainted by oil.

This study assumed that responsive action were taken on board ship by immediately treating oil with chemical dispersant through the existing piping system, trying to enhance the effectiveness of environment recovery. The aim of this experimental study was mainly to compare the movement of dispersed oil into marine sediment under two different dispersant application scenarios, application prior to and after oil being spilled overboard.

2. Experimental

2.1. Pre-spill and post-spill application

Dispersant was premixed with oil to simulate the situation of dispersant applied to oil on board ship prior to entering into the sea. In contrast, to simulate the scenario which is common in oil spill response, i.e. dispersant application being carried out for a certain period of time after oil is spilled overboard and enters the sea, oil was applied to the test chamber followed by dispersant application.

It is common practice on board ship to heat fuel oil prior to transferring and injecting for combustion in the engine or boiler furnace. One of the experiments in this study was to find out how the effectiveness of dispersion may be influenced by

the fuel oil temperature, i.e. heated oil. In this experiment, the dispersant/oil ratio was maintained at 1/10.

2.2. Sediment collection

Marine sediments were collected with a 0.2-m² grab, from ShenAu Beach of Taipei County, Taiwan, on December 6, 2002. Approximately 5 kg of sediment were collected from the top 2 cm of several grabs at six stations (about 5–6 m apart) along the beach. The sediment was thoroughly homogenized, placed in containers, and stored in an ice chest for transport back to the laboratory. Sieves were used to separate sediment fractions greater than 6 mm and pipette analysis was used to measure smaller fractions. Three replicates were used in the data analysis.

2.3. Oil and dispersant samples

Marine fuel oil (bunker “C”) was obtained from six cargo ships currently under operation. Table 1 shows the typical properties of the marine fuel oils tested. Dispersant was purchased from a local supplier. The supplier would not release any details and even the brand name of the dispersant, for reasons of commercial confidentiality.

2.4. Preparation for test chambers and oil dispersion

For intertidal sediments, a 12-cm layer of sediment was placed in an open-bottom (meshed) tray in a glass chamber of 500 mm × 250 mm × 400 mm filled with a volume of about 30 liters of water. The test chamber was shaken on a to-and-fro platform shaker (12 cycle/min) right after oil (and dispersant) application, before sampling for sediment. The shaking movement was limited to ensure that the sediment layer in the test chamber was kept stable. In the chamber tests, it was subjected to some form of turbulent mixing by pumping.

The preparation of oil dispersions in various mixing chambers was complicated by interactions between the three phases (oil, water, and dispersant) and the chamber walls that were complex and difficult to reproduce.

Table 1
Typical characteristic of the tested fuel oils

Fuel oil ^a	Maximum	Minimum	Average
Gravity API at 15.6 °C	21.0	17.0	18.5
Viscosity cSt at 15 °C	193.9	44.27	131.1
Water content (vol%)	0.20	Trace	0.10
Solid and water (vol%)	0.50	0.20	0.28
Pour point (°C)	5	–16	–9
Flash point (PM) (°C)	156	76	100

Source: Ship A, Tank No. P36 P37, Ship B, Tank No. P35, Ship C, Tank No. S3, Ship D, Tank No. P6, Ship E, Tank No. P16.

^a High sulfur HFO.

2.5. *Tidal flushing and sediment sampling*

To simulate the intertidal zone, all water was drained out through the sediment bed. Tidal flushing was simulated in each tank, with a gentle exchange of water through the sediment to prevent the formation of an anaerobic deeper layer.

To determine how tightly the dispersed oil was bonded to the surface of sediment particles, special cores were prepared. Sediment cores were obtained at different depths right after water drained through the sediment bed at atmospheric pressure. The corer was hand-made from a 25-mm diameter stainless tube. Ten sediment samples for each type of treatment were taken such that five of each would serve as initial values and the other five as final values after receiving a flush with water, where water was freely drained through the sediment layer under atmospheric pressure.

2.6. *Use of soap water as replacement for chemical dispersant*

Limited by storage space and cost, it is reasonable to believe that in practice, few ships actually store sufficient chemical dispersant for oil spill response. As an alternative, soap may be considered as a replacement for chemical dispersant.

Based upon practical experiences of using laundry soap water for treating floating fuel oil, soap water at concentrations of 0.5 and 1.0 g/ml water were pre-mixed with crude oil for the pre-spill application scenario. The soap tested was an ordinary laundry soap purchased from a grocer.

2.7. *Quantitative analyses of oil components in sediment*

Sediment samples were extracted with CCl_4 for oil content analysis. They were pre-mixed with CCl_4 and shaken vigorously for 2 min. To determine the effectiveness as affected by duration and temperature of extraction, sediment was repeatedly extracted at least four times.

Analyses of tested oil dispersions were conducted using the infrared spectroscopic technique (Yanagimoto OIL-103 Oil Analyzer), confirmed by gas chromatography (Hewlett Packards 830A, FID, 50 °C at injection port, carrier gas: helium, 1 ml/min). Solid phase microextraction (SPME), a simpler and faster method was used for sample preparation. Infrared has been popular and proven to be acceptable (Anderson et al., 1989). A major portion (96% in average) of hydrocarbon oil was washed out from sediment by two CCl_4 extractions. The same steps were followed for analyzing oil in sediment throughout this investigation.

In the experiment for stability, the requirement set-up for the reproducibility of the test was that the results of four successive runs had to be within 10% of each other. Thus, each treatment was repeated at least four times. The data obtained were expressed as the percentage of oil dispersed and treated statistically to identify “outliers” in the material.

3. Results and discussions

3.1. Sediment chemistry

Reasonable estimation of the sorption behavior of hydrophobic pollutants could be made from knowledge of the particle size distribution and associated organic carbon contents of the sediment and the octanol/water distribution coefficients of the pollutants (Karickhoff et al., 1989). The sediment chemistry for these laboratory experiments was as given in Table 2. It was dried at 76 °C overnight to eliminate indigenous bacteria from the soil.

The sediment had relatively high amounts of sand (56%) and medium fine particles (33%). It was tested together with commercially available artificial sands, which functioned as control sediments. This procedure eliminates problems caused by pockets of low and high hydrocarbon concentrations on or beneath the surface created by oiling, as have occurred in many early experiments.

In addition to affecting the movement of pollutants, sorption could be involved directly in pollutant degradation via surface-associated chemical processes. In Bragg and Yang's (1999) study, it was recognized that natural sediments could indirectly mediate solution-phase processes by altering the pollutant concentration in solution or by providing a buffered solution-phase ion suite that may affect the dielectric properties and acidity of the solution phase. This explains how and why residual oil is removed from shorelines in the absence of hydraulic activity, e.g. waves and currents.

3.2. Dispersion stability

Since it is a common practice on board ship to heat fuel oil in the storage tank before transferring for combustion, in the pre-spill-application scenario study fuel oil was kept at temperatures of 20, 30, 40, and 60 °C in a water bath before mixing with dispersant. Fig. 1 shows the percentage of dispersed fuel oil for different temperatures (20 through 60 °C) and different sources (Ship A through F) after 12 min of settling. It can be seen that in general, when the dispersant/fuel ratio was within the range of 1/10 and 1/20 (0.1 and 0.05), fuel oil with higher temperature yielded higher dispersion, especially when fuel oil was heated to 60 °C. However, as a rule for all fuel sources and temperatures, when the dispersant/fuel oil ratio decreased to 1/50, the dispersion percentage dropped to only about 20%. In addition, fuel oil

Table 2
Sediment chemistry for laboratory experiments

Batch no.	Total organic carbon (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Nitrogen (%)	Available phosphate (%)
1	2.19	5.42	61.6	25.4	7.58	0.11	11.6
2	1.83	3.39	58.9	26.2	11.5	0.90	13.8
3	1.67	4.44	60.0	22.1	13.5	0.12	9.81
4	2.08	5.02	51.1	19.8	24.1	0.13	12.8

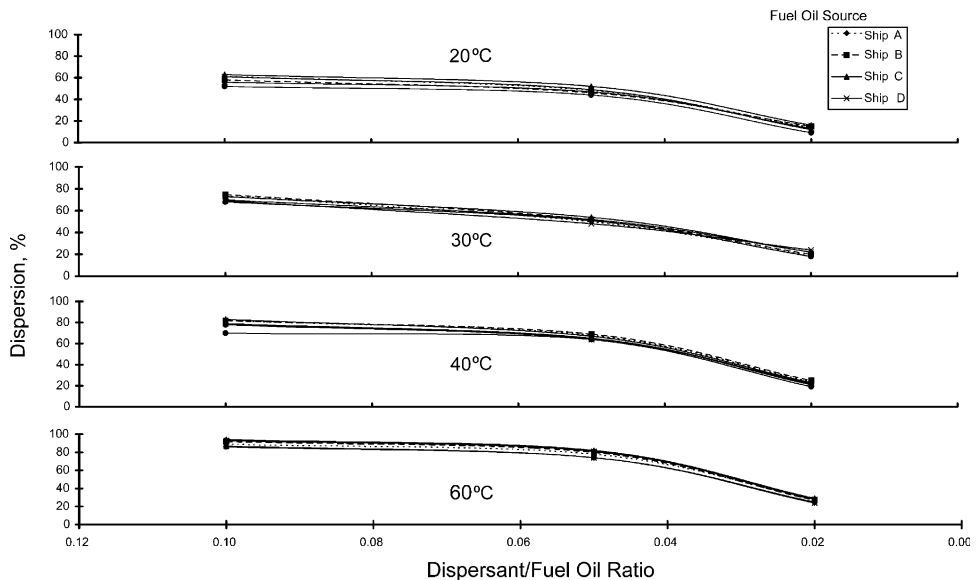


Fig. 1. Percentage of dispersed fuel oil of different temperatures and different sources after 15 min of settling.

from Ship B had markedly higher dispersion than fuel oil from other ships at 40 °C, whereas when heated up to 60 °C fuel oil from various sources yielded stable and the highest (above 80%) dispersion for a dispersant/fuel oil ratio above 1/20. This result suggested that under a storage temperature of 60 °C, the dispersion of fuel oil may be maximized if a dosage of 1/20 dispersant was pre-applied prior to spilling into the sea.

The stability of the dispersion obtained was defined as the ratio of the amount of dispersed oil after 15 min settling to the amount of originally dispersed oil tested. This specific length of time was chosen after an initial test series where the settling time needed to achieve balance in the oil/water/dispersant mixture was determined according to Fig. 1. The dispersion stability data gave a clue as to what kind of dispersion was formed, and thus an indication of what might happen initially at sea. The results showed that it was important to screen the effectiveness of various dispersant to find a good formulation for extreme conditions.

3.3. Effectiveness test

In this study, the effectiveness test procedure was carried out according to Mackay and Szeto (1981), Mackay et al. (1982). Water temperatures were maintained separately as required through temperature controllers within ± 1 °C. Fig. 2 compares the effectiveness of dispersion for fuel oil from different sources measured by the amount of dispersed oil (as a percentage of the amount originally dispersed) after 30 min of settling. The dispersant tested in this study demonstrated rather

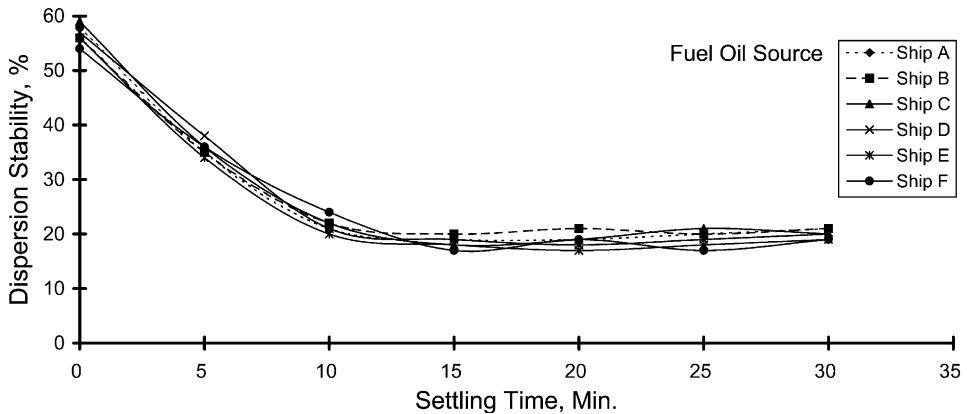


Fig. 2. Dispersion stability of marine fuel oil of different sources after 30 min of settling.

similar effectiveness for different sources of marine fuel oil samples. The relative oil/dispersant temperature was important for the performance of the chemicals. In McDonald's (1984) investigation, when the temperature of the dispersant was decreased from 15 to 4 °C, the effectiveness of the dispersant decreased from 56% to 40%.

Based upon the results obtained in this study, it is apparent that the “warmer” the fuel oil the higher the dispersion effectiveness yielded. This relationship is more significant at higher dispersant dosage (e.g. D : O = 1/10) than at lower dosage (e.g. D : O = 1/50). Although not all fuel oil showed higher effectiveness when fuel oil temperature was raised from 30 to 40 °C, it was quite clear that effectiveness was significantly enhanced when fuel oil was heated up to 60 °C.

3.4. Adsorption characteristics of dispersed oil as affected by water temperature

In this study, dispersed oil in water was gradually drained through a bed of sediment at atmospheric pressure to investigate the depth of oil penetration. Fig. 3 illustrates the oil contents in sediment (mg/kg), sampled from different depths (top, 4.5, 7.5, 10.5 cm) at three water temperatures (10, 30, 40 °C), after five flushes. Note that the scale shown here for oil content in the top layer of the sediment bed is 10 times (up to 20,000 mg/kg) that in deeper layers (up to 2000 mg/kg).

There was rather high variability among various water temperatures in the concentration of absorbed oil in top sediment than in deeper layers, following first flush. Oil distribution in the top sediment layer was, however, consistently related to the oil concentrations at deeper sediment layers. The loss of dispersed oil following first flush was apparent in the surface sediment. No more loss of dispersed oil from the top layer was observed after second and third flush. In bottom sediments, the dispersed oil increased with first flush. It remained pretty much the same thereafter, even when followed by five flushes. These results implied that in the field condition, most dispersed oil would be flushed from the top sediment layer to

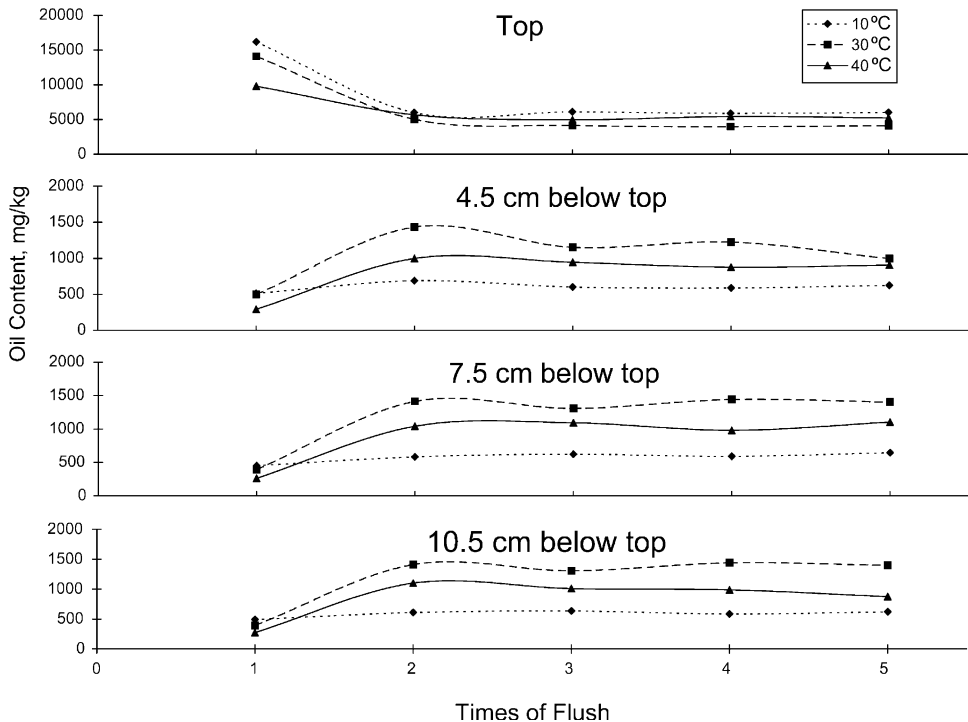


Fig. 3. Oil content in sediment, at different depths at three water temperatures after five times of flushing.

the bottom by the tide right after oil spill incidents, if dispersant was applied effectively.

To further understand the adsorption characteristics of the dispersed oil in sediments, control and treated sediments were flushed at atmospheric pressure for the same period. When only oil was mixed with sediment, the flush caused about 31% of the absorbed oil to be washed away. The 1/10 dispersant to oil mixture produced a 40% loss during flushing.

Dispersed oil demonstrated rather similar behavior in deeper layers (4.5 cm and below) of marine sediment following successive flushes. The experiment showed that the water temperature affected the fate of dispersed oil in surface and deeper sediment layers differently.

At 10–30 °C as much as twice the dispersed oil was retained in the top sediment after first flush compared to the case at 40 °C. After second flush the oil retained in the top sediment dropped and remained the same thereafter regardless of whether more flushes followed. Such a decrease in oil adsorption to the top layer of the sediment was accompanied by a two to three times increase of oil content in deeper (below 4.5 cm) layers. But the oil content in the deeper layers is stabilized as well.

In the sediment layer 4.5 cm below surface, oil content increased sharply in 30 and 40 °C water following second flush. In contrast, in 10 °C water, the oil content

in deeper sediment was consistently maintained at the lowest level (approximately 500 mg/kg), suggesting that the dispersion of oil was markedly restricted by low temperature. Dispersed oil was much less mobile and contributed little to deeper sediment with successive flushing. This result seemed to agree with McDonald's (1984) finding. However, it was observed that water temperature did not play an important role in affecting the behavior of dispersed oil at the surface layer of the sediment before water temperature was raised to 40 °C.

In the literature, the relative effect of temperature on oil and dispersant has been widely discussed and conclusions have usually been made that dispersants are less effective at lower temperatures. However, Cox (1981) and Schultz (1981) as well as Zitko and Carson (1969) have obtained contradictory results in that increased effectiveness was shown as a result of decreased dispersant temperature. It was suspected that the solvent base of the dispersant may be the reason, that is, dispersants that are water-miscible and -immiscible behave differently, specifically at low temperature.

In general, the adsorption of dispersed oil to marine sediment reached a stable condition and most oil residue was retained in deeper layers after second flush. It can be seen that in cold (10 °C) water, the top sediment yielded the highest oil content throughout five flushes while below, it was consistently lowest. This may suggest that in water at a temperature as low as 10 °C, due to lower dispersion, the dispersed oil if it were not lost following first flush, will be mainly retained in the top layer of the marine sediment after all. Based upon the results, the background of oil content in sediment was as high as approximately 50 mg/kg.

There was another clue showing that water temperature played an important role in affecting the dispersion behavior of dispersed oil in water. Oil dispersed evenly at higher temperatures (30 and 40 °C), while it tended to flocculate at lower temperatures (10 °C). In Fig. 3, it can be seen that, after first flush, the retention of dispersed oil in the top sediments decreased with higher temperature. However, after second and third flushes, the influence of temperature on the adsorption characteristics of dispersed oil to top sediment was almost negligible. Dispersed oils were virtually retained in the top sediment after first flush even when the water temperature was increased from 10 to 30 °C. However, oil retained in sediment decreased noticeably after first flush at a water temperature of 40 °C, implying that the retention capability of dispersed oil in marine sediment was diminishing with increase in water temperature, within certain temperature ranges (e.g. 30–40 °C).

3.5. Movement of dispersed oil in sediment under pre- and post-spill application scenario

The major objective of this study was to compare the movement of dispersed oil at different water temperatures (5, 10, 20, 30, 40 °C) in sediment under pre- and post-spill application scenarios. Fig. 4(a)–(d) present the comparison for the behavior of marine fuel at four temperatures (20, 30, 40, 60 °C), respectively.

Similar to the findings in the dispersion effectiveness study, much more oil was retained in the top sediment layer than in deeper beds under all circumstances.

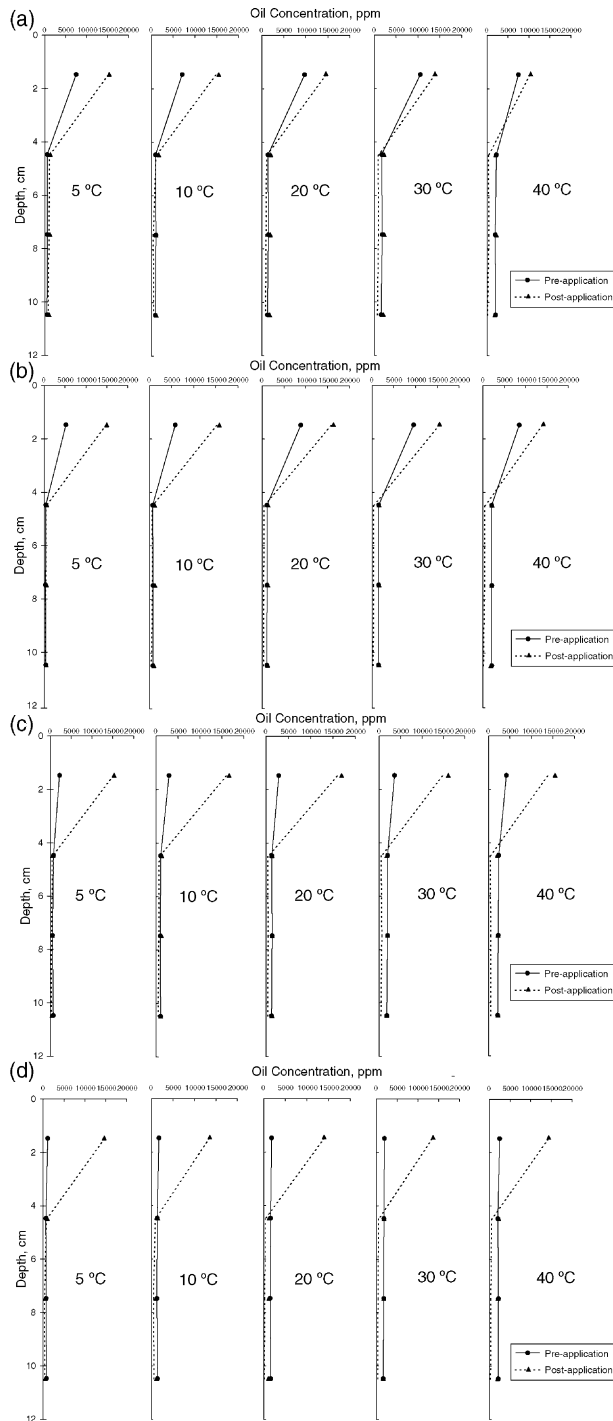


Fig. 4. Comparison of behavior of dispersed oil in sediment under pre- and post-application scenario for marine oil fuel at the five fuel temperatures (a) 20 °C, (b) 30 °C, (c) 40 °C and (d) 60 °C.

It was also obvious that the pre-spill application scenario retained much less (1.5–3 order of magnitude) oil than the post-spill scenario in top sediment. In deeper (below 4.5 cm) sediments, almost only trace oil was retained, although pre-spill application retained more oil than the post-spill application scenario here. These results suggested that much higher dispersion could be obtained when using the pre-spill application (i.e. apply dispersant to oil prior to spilling overboard) strategy.

Marine fuel oil may be stored on board ship at temperatures as low as about 10 °C to as high as 60 °C depending on factors such as tank location, sea water temperature, and heating procedure. In this study, fuel temperatures of 20, 30, 40, and 60 °C were tested. Based upon the result, the difference of oil retention in top sediment between the pre- and post-spill application scenario increased with increase in fuel oil temperature. However, for fuel oil at 20 and 30 °C (Fig. 4(a),(b)) the effect of pre-spill application was not as apparent as that for fuel oil at 40 and 60 °C (Fig. 4(c),(d)). This can be explained by the improvement in the effectiveness of dispersion in fuel oil with higher temperature and accordingly lower density. As a rule as concluded in earlier studies (Cox, 1981; Schultz, 1981) about the reaction of dispersion with oil, dispersant may penetrate easier into oil with lower density and disperse it more effectively. In this study, when fuel oil was heated up to 40 °C, and further to 60 °C, and premixed with dispersant, it was very likely that oil was mostly well dispersed and would largely pass through the sediment bed with drainage.

It was interesting to compare the water temperature effect on the fate of dispersed oil under pre- and post-spill application scenario, when different fuel oil temperatures were introduced in this experiment as shown in Fig. 4. For fuel oil at lower temperatures (20, 30, and 40 °C), the effectiveness of pre-spill application was not as significant at higher temperature than at lower water temperature. However, for warmer (60 °C) fuel oil, the difference in the effect of the pre-spill application strategy under various water temperatures was negligible. As fuel oil was heated up to certain degree, almost all of it was dispersed and easily drained through the sediment bed, and water temperature was therefore no more an important role in affecting the movement of oil in sediment.

Since other factors by which the adsorption of oil to sediment may be influenced were kept the same, it is reasonable to presume that the effectiveness of dispersion was in fact the major factor in influencing the movement of dispersed oil in the sediment layer.

3.6. Use of soap water as replacement for chemical dispersant

Again, in practice the availability of chemical dispersant on board ship may be doubtful; soap water was thus tested as a replacement for chemical dispersant in this study. In this certain test, sediment was repeatedly flushed at a flow rate of 30 ml/min, and water temperature was maintained at 29 ± 1 °C. Fig. 5 shows the testing results. The performance of soap water in affecting the oil characteristics in

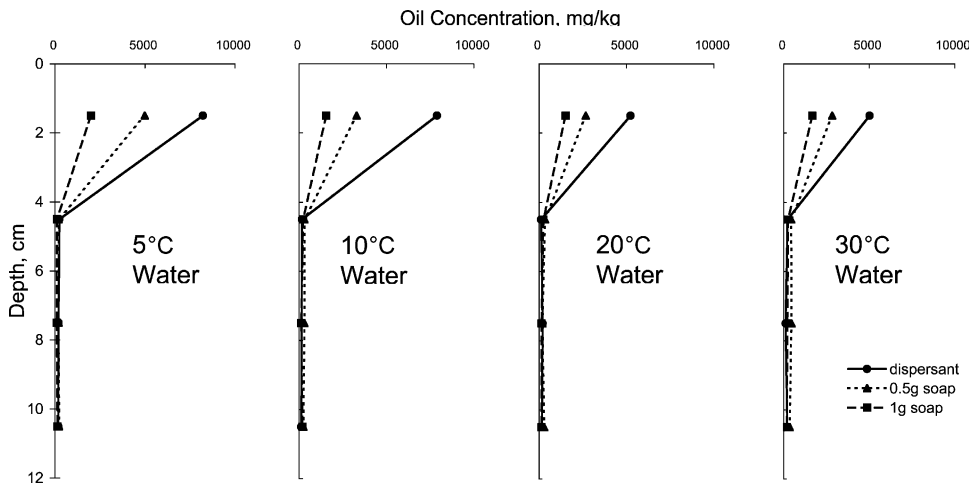


Fig. 5. Adsorption of oil dispersed by soap water and chemical dispersant at various water temperatures.

marine sediment was rather similar to that of the chemical dispersant used in this study.

It was observed that surprisingly, when soap water (0.5 g/ml) was used as replacement for chemical dispersant, almost one-half as much oil was retained in the top sediment as that when using chemical dispersant consistently at four water temperatures. It is suggested that with this dosage, soap water worked better than chemical dispersant in oil dispersion. This difference was more noticeable at water temperatures of 5 and 10 °C than at 20 and 30 °C. Only trace oil was analyzed in deeper sediments following first flush, under all circumstances.

When soap dosage was doubled, the adsorption of dispersed oil to top sediment was almost proportionally decreased. The effect of soap dosage was more marked at low water temperature than at high temperature. Although using soap water as replacement for chemical dispersant may not be a common practice currently, it is certainly worthwhile to evaluate further the side effects and furthermore, the possibility of its wide use.

4. Conclusion

This experimental study shows that the immediate response, on board a ship facing possible oil spill, of applying dispersant prior to oil being spilled overboard can result in an enhanced oil dispersion which may further benefit environmental recovery. The pre-spill application scenario retained much less oil than the post-spill scenario in the top sediment. The difference of oil retention in top sediment between the pre- and post-spill application scenario increased with increase in fuel oil temperature. For fuel oil above 40 °C, the difference in the effect of pre-spill application strategy under various water temperatures was negligible. When soap

water was used as replacement for chemical dispersant, almost one-half as much oil was retained in the top sediment as that for using chemical dispersant. The adsorption of dispersed oil to the top sediment almost proportionally decreased with doubling of soap dosage.

Acknowledgements

I acknowledge the Yang Ming Navigation Company for the contribution of marine fuel oil samples from their container ships.

References

- Anderson, J.W., Kiesser, S.L., Rappports, J.W., 1989. Et Proces-verbaux des Reunions. In: Conseil Permanent International pour l'Exploration de la Mer, 179, pp. 62–70.
- Bailey, R.C., White, D.W., 1970. Methods of analysis for petroleum hydrocarbons. In: Malins, D.C. (Ed.), *Effects of Petroleum on Arctic and Sub-Arctic Marine Environments and Organism*, 1, pp. 31–62.
- Bragg, J.R., Yang, S.H., 1999. Clay–oil flocculation and its role in natural cleansing in Prince William Sound following the Exxon Valdez oil spill. In: *Exxon Valdez Oil Spill in Alaskan Water*, ASTM Papers.
- Cox, J.H., 1981. Field experiments on the effects of crude oil and dispersant on the common animals and plants of rocky seashores. *Marine Environmental Research* 8 (4), 215–239.
- Harris, G.W., Wells, P.G., 1979. A laboratory study on the adhesion of crude oil to beach sand in the presence of a dispersant. *Spill Technology Newsletter* Sep-Oct, 293–298.
- Karickhoff, S.M., Brown, D.S., Scott, T.A., 1989. Sorption of hydrophobic pollutants on natural sediments. *Water Research* 13, 241–248.
- Little, D., Baker, J.M., Abbiss, T.P., Rowland, S.J., Tibbetts, P.J.C., 1986. In: Mackay, D., Wells, P.G., Paterson, D. (Eds.), *Chemical Dispersion of Oil Spills*. Institute for Environmental Studies, University of Toronto, Ontario, Canada, pp. 117–151 (Publication EE-17).
- Mackay, D., Szeto, F., 1981. The laboratory determination of dispersant effectiveness: method development and results. In: *Proceedings of the 1981 Oil Spill Conference*, API, Washington, DC, pp. 11–18 (Publication 4334).
- Mackay, D., Chang, S., Wells, P.G., 1982. Effectiveness of oil spill chemical dispersant. *Marine Pollution Bulletin* 13 (8), 1071–1086.
- Mackay, D.A., Chau, K.H., Bobra, M., 1984. Measurement and prediction of the effectiveness of oil spill chemical dispersant. In: Allen, T.E. (Ed.), *Oil Spill Chemical Dispersants: Research, Experience and Recommendations*. ASTM, Philadelphia, pp. 38–54.
- McDonald, J.M., 1984. Growth simulation following oil pollution. In: Cowell, E.B. (Ed.), *The Ecological Effects of Oil Pollution on Littoral Communities*. Institute of Petroleum, London, pp. 72–77.
- Owens, E.H., 1999. The interaction of fine particles with stranded oil. *Pure Applied Chemistry* 71 (1), 83–93.
- Pionke, G.B., Chester, D.J., 1973. The distribution of intertidal organisms along the coasts of the English Channel. *Journal of the Marine Biological Association of the United Kingdom* 37 (1), 157–208.
- Schultz, T.P., 1981. The fate and effects of dispersant-treated compared with untreated crude oil. In: *Proceedings of the Arctic Marine Oil Spill Program 4th Annual Technical Seminar*, Environmental Protection Service, Ottawa, pp. 401–443.
- Zitko, V., Carson, B.D., 1969. Effects of dispersant concentrations on marine organisms in the field. *Marine Pollution Bulletin* 10 (4), 100–103.