EXPERIMENTAL STUDY ON SPREADING OF OIL SPILLED AMONG PACK ICE

Natsuhiko Otsuka1, Kouji Ogiwara2, Kohei Kanaami3, Shinjiro Takahashi4 and Hiroshi Saeki3

ABSTRACT
In order to determine the characteristics of the spread of crude oil in seawater with pack ice, experiments were carried out using model pack ice made of circular ice plates under various conditions of oil discharge rate, oil volume and ice concentration. Results of experiments in which the ice concentration was small showed that the spilled oil spread between ice plates but that the rate of spread was much less than that in the case of open water. On the other hand, when the ice concentration was high and there were isolated areas of open water, spilled oil spread by overtopping the parts of the circular ice plates that were in contact with each other and oil was trapped in the isolated open water areas. The characteristics of the spread of spilled oil depend on the density and concentration of ice, density and viscosity of oil, and net surface tension between ice, oil and water.

INTRODUCTION
Extraction of crude oil from the northeastern shelf off Sakhalin Island in the Sea of Okhotsk started in the summer of 1999. Transportation of the crude oil by oil tankers has only been possible during the period from July to November because of the blockage caused by ice floes in winter. However, it has been planned to continue extracting crude oil year-round by constructing an underwater pipeline. This will involve a risk of oil spillage accidents occurring in the winter in the Sea of Okhotsk, when the sea is covered with ice. Ice floes in the Sea of Okhotsk consist of ice sheets of various shapes, and the concentration of ice floes varies greatly. If an oil spill occurred under the ice-covered sea, the oil would spread beneath the ice cover. If, however, the ice floes did not completely cover the water surface, the oil would spread through the areas of open water between the ice sheets.

The characteristics and mathematical modeling of radial spreading of oil under a flat ice sheet have been studied by laboratory experiments (Yapa and Chowdhury, 1990), and the characteristics of oil spreading under broken ice were studied by Yapa and Weerasuriya

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(1997). Otsuka et al. (2001) carried out an experimental study on the spread of oil under uneven ice sheets. However, spread of oil in the case of loosely packed ice floes and spread of oil in the case of existence of open water between ice sheets were not considered in those studies. Sayed and Ng (1993) carried out an experimental study on spread of oil over and between densely packed ice floes. Buist and Bjerkelund (1986) carried out a field experiment on spread of oil between pack ice. In their study, 1 m$^3$ of crude oil was discharged into pack ice of different concentrations. It was found that the area over which the oil spread and the rate of spread were much less than those estimated by a theoretical model in open water (Fay, 1971). However, little is known about the spread of oil in the sea between sheets of pack ice such as those in the Sea of Okhotsk. The aim of this study was therefore to determine the characteristics of the spread of crude oil on the surface of water between sheets of pack ice with various concentrations. Experiments were carried out using model pack ice made of circular ice plates under various conditions of oil discharge rate, oil volume and ice concentration to determine the characteristics of the spread of oil in seawater with pack ice.

**EXPERIMENTAL METHOD**

A round glass-bottomed steel tank of 1.6 m in diameter and 0.8 m in depth was used to observe the spreading of oil (Fig. 1). The tank was filled with 3 % saline water cooled to −5 degrees. Model pack ice was made using circular plates of frozen saline water measuring 3 cm in thickness and 10 cm in diameter. As shown in Fig. 2, experiments were conducted with ice concentrations of 90 %, 60 % and 0 % (no ice). In the case of ice concentration of 90 %, the ice plates were in contact with each other, thus creating open water areas only in the gaps made by the curves of the circular ice plates. In the case of ice concentration of 60 %, the ice plates were not in contact with each other (narrowest gap between the ice plates being 1 cm), thus creating a continuous area of open water between the ice plates. In this case, the ice plates were fixed by thin foam polystyrene rods.

![Figure 1: Experimental apparatus](image1)

![Figure 2: Arrangements of model pack ice](image2)

In the experiment, Iranian Light crude oil was injected at a constant rate under the model pack ice using an air compressor. The subsequent spreading of oil, which could be viewed through the glass tank bottom, was recorded by a video camera, and the spreading velocity and area were measured. The experimental conditions are summarized in Table 1.
Table 1: Experimental Conditions

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3-1</th>
<th>Case 3-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration of model pack ice</td>
<td>0 %</td>
<td>60 %</td>
<td>90 %</td>
<td>90 %</td>
</tr>
<tr>
<td>Oil temperature</td>
<td>1</td>
<td>–0.5</td>
<td>–0.5</td>
<td>–2.5</td>
</tr>
<tr>
<td>Oil viscosity (mPa*s)</td>
<td>95</td>
<td>190</td>
<td>145</td>
<td>118</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.876</td>
<td>0.876</td>
<td>0.876</td>
<td>0.876</td>
</tr>
<tr>
<td>Oil volume (l)</td>
<td>0.079</td>
<td>0.157</td>
<td>0.157</td>
<td>0.864</td>
</tr>
<tr>
<td>Discharge rate of oil Q (l/s)</td>
<td>0.00248</td>
<td>0.00193</td>
<td>0.00442</td>
<td>0.01542</td>
</tr>
<tr>
<td>Saline temperature</td>
<td>0.2</td>
<td>–0.5</td>
<td>–0.5</td>
<td>–0.5</td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS

Case 1 (without ice; ice concentration = 0 %)
Since no ice plates were used in case 1 (ice concentration of 0 %), the oil was injected in open water. Fig. 3 shows a photo of the oil slick just after termination of the injection of oil, and Fig. 4 shows a photo of the oil slick at 810 seconds after termination of the injection of oil. In case 1, the oil rapidly spread over the water surface just after termination of the oil injection. The final average thickness of the oil slick was 0.05 mm. However, it is thought that an oil slick in open seawater would become thinner.

![Figure 3: Spread of oil in case 1](just after termination of oil injection) ![Figure 4: Spread of oil in case 1](810 seconds after termination of oil injection)

Case 2 (ice concentration = 60 %)
Fig. 5 and Fig. 6 show photos of the spread of oil in case 2 (ice concentration of 60 %) just after termination of the injection of oil and at 40 minutes after termination of the injection of oil, respectively. As can be seen in the photos, the oil spread between the ice plates and continued to spread after termination of the injection of oil but did not spread through gaps between ice plates of less than 0.5 cm. The oil then spread beyond the ice plates, though not as rapidly as in case 1 (open water), and the spread of oil finally stopped (Fig. 7).

Case 3 (ice concentration = 90 %)
Two experiments were carried out for case 3 (ice concentration of 90 %): one experiment using a small amount of oil and low rate of injection (case 3-1) and one experiment using a large amount of oil and high rate of injection (case 3-2). Fig. 8 and Fig. 9 show photos
of the spread of oil in case 3-1 at 60 minutes after termination of the injection of oil and in case 3-2 at 90 minutes after termination of the injection of oil, respectively.

In case 3-1 (small amount of oil and low rate of injection) the oil spread to adjacent open water areas by overtopping the parts of the ice plates in contact (Fig. 10). And the oil did not stall beneath the ice plate but was trapped into the open water area that circumscribed by the ice plates. In case 3-2 (large amount of oil and high rate of injection), the oil spread

Figure 5: Spread of oil in case 2 (just after termination of oil injection)

Figure 6: Oil spreading on case 2 (40 min after termination of oil injection)

Figure 7: Spread of oil beyond the pack ice

Figure 8: Spread of oil in case 3-1 (60 minutes after termination of oil injection)

Figure 9: Spread of oil in case 3-2 (90 minutes after termination of oil injection)

Figure 10: Oil that overflowed into the open water area in case 3-1
from the injection point over the upper surface of the ice plates, and the peripheral part of
the oil slick spread by overtopping the parts of the ice plates in contact as in case 3-1. The
blackened areas of the ice plates in the photo are the areas in which the oil spread over the
ice plates.

DISCUSSION
Spread of oil under the condition of discharge of oil at a constant rate
The rates of oil injection in the experiments are shown in Table 1. Fig. 11 shows the
changes in the areas of oil slicks with elapse of time under the condition of discharge of
oil at a constant rate. The area of the oil slick was measured by counting the number of
pixels in graphical data. As the data in the figure indicate, the slick area expanded at an
almost constant rate and the rate of oil spread between the ice plates was only about one
tenth of that in open water (case 1). Figure 12 shows the changes in thicknesses of oil
slicks with elapse of time under the condition of discharge of oil at a constant rate. The
thickness of the oil slick was calculated by dividing the slick area by the volume of oil. As
the data in the figure indicate, the thickness of the oil slick remained almost constant
throughout the entire period of oil discharge except for the beginning of oil injection.

Characteristics of spread of oil under the condition of a constant volume of oil
Fig. 13 and Fig. 14 show the changes in the areas of oil slicks and the changes in
thicknesses of oil slicks with elapse of time under the condition of a constant volume of
oil, respectively, and Table 2 shows the final slick thicknesses. The oil spread gradually
after the termination of oil injection and the spread of oil stopped after some time. The
final oil slick area in case 2 was larger than that in case 3-1. Since the same volumes of oil
were injected in these two cases, this result indicates that the final oil slick area is smaller
the greater the ice concentration is. The final oil slick thickness in the case of ice
concentration of 90 % was 60-times greater than that in the case of open water and
10-times greater than that in the case of ice concentration of 60 %. These results indicate
that the greater the ice concentration is, the greater is the final oil slick thickness.

In case 2, the spread of oil between the ice plates stopped when the gap between the ice
plates was less than 0.5 cm. In this case, the force accelerating the spread of the oil slick is
buoyancy force (gravity force), and the forces that retard spreading are surface tension
acting on the surface of the oil slick above the water and on the surface between the oil
and water, and interfacial tension between the oil and ice plate acting on both ends of the
gap. If the gap between ice plates is small, it is thought that interfacial tension between the oil and the ice plate and surface tension of the oil slick create a balanced force that acts in an arch manner against the buoyancy force, thus causing the spread of oil in narrow gaps between ice plates to stop (Fig. 15).

Figure 13: Changes in areas of oil under the condition of a constant volume of oil

Figure 14: Changes in thicknesses of oil under the condition of a constant volume of oil

Table 2: The final slick thickness

<table>
<thead>
<tr>
<th>Case</th>
<th>Ice concentration</th>
<th>Oil slick thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0 %</td>
<td>0.05mm</td>
</tr>
<tr>
<td>Case 2</td>
<td>60 %</td>
<td>0.5mm</td>
</tr>
<tr>
<td>Case 3-1</td>
<td>90 %</td>
<td>3.0mm</td>
</tr>
<tr>
<td>Case 3-2</td>
<td>90 %</td>
<td>3.3mm</td>
</tr>
</tbody>
</table>

Figure 15: Interfacial tension acting on gaps between ice plates

**Scale effects**

Fay (1971) proposed a theory regarding the spread of oil on the surface of water in which the spread of oil is divided into three phases. Immediately after a spill, the oil slick is relatively thick, and the spread of oil is accelerated by gravity (buoyancy) force and
retarded by inertial force (phase 1). As time elapses and the oil slick becomes thinner, viscosity force predominates over inertial force as a retarding force (phase 2). As the oil slick thins further, surface tension and viscosity become the prevailing forces (phase 3). As a step toward elucidation of the mechanisms of spreading of oil spilled under flat ice sheets, Yapa and Chowdhury (1990) derived equations from Fay's theory for the slick radius at which the spreading terminates and for the time until spreading terminates using models in which the spreading stops due to a balance between interfacial tension and buoyancy.

However, the scaling effect is a problem in modeling and experimental studies on the process by which oil spilled in icy seawater. An ideal solution is to conduct experiments using conditions that correspond exactly with physical conditions in the field and to tune up the coefficient between experimental and real-scale phenomena by using field data. Froude similitude can be used in the case of oil spreading in open water in phase 1, but Reynolds similitude should be used in phase 2, in which viscous force is dominant. In phase 3, in which surface tension force is dominant, the Weber number should be matched. However, considering those scale effects, it is very difficult to control oil volume, oil viscosity, and interfacial tension between oil, ice and water in laboratory experiments. Therefore, the series of experiments carried out in the present study are considered to be very small-scale actual spills.

**Comparison of experimental results and field data**

In field tests on oil spilled in water between pack ice conducted by Buist and Bjerkelund (1986), crude oil of almost the same viscosity as that of the oil used in this study was released into a pack ice field of concentrations of 50 % and 90 %. The ice floes ranged from small pancake-like structures to large floes of 5 to 28 m in diameter and 0.5 to 1.6 m in thickness. The mean size of ice floes in southern Okhotsk Sea was reported by Toyota and Enomoto (2002) to be about 100 m, and the mean thickness was reported by Uto and Shimoda (2000) to be about 0.5 m. It is thought that the conditions of the pack ice in the field tests conducted by Buist and Bjerkelund (1986) are similar to those of pack ice in the Okhotsk Sea and that their field test data can therefore be applied to an oil spill in the Okhotsk Sea. In their field tests, the final oil slick thickness was 0.04 to 0.2 mm at an ice concentration of 50 %. In the present study, however, the oil slick thickness in case 2, in which the ice concentration was 60 %, was 0.5 mm. Moreover, in their field test conducted in an ice field with an ice concentration of 90 %, most of the gaps between ice plates were covered by brush ice and the oil slick thickness was 1.5 to 3.0 cm. This range of oil slick thicknesses is similar to the range of thicknesses of oil slicks under ice floes reported by Otsuka et al. (2001). In the present study, however, the oil slick thickness in cases 3-1 and 3-2, in which ice concentration was 90 %, was about 3 mm. From these results, the magnitude relation of oil slick thickness responds to the ice concentration is consistent in spite of scale difference between laboratory experiment and field test.

**CONCLUSION**

A series of experiments on the characteristics of oil spread were carried out using model pack ice made of circular ice plates under various conditions of oil discharge rate, oil volume and ice concentration. The following results were obtained.

1. In an experiment in which the ice concentration was small and there was a continuous area of open water between ice plates, the oil spread between the circular ice plates
arranged in a lattice pattern. The oil continued to spread after the termination of oil injection but stopped at gaps of less than 0.5 cm between ice plates, suggesting that interfacial tension between ice and oil plays a role in the balancing of force against buoyancy force, which accelerates the spread of oil.

2. In the case in which the ice concentration was high and open water areas only existed in the gaps made by the curves of the circular ice plates in contact with each other, the oil spread to adjacent open water areas by overtopping the parts of the ice plates in contact. And the oil did not stall beneath the ice plate but was trapped into the open water area that circumscribed by the ice plates.

3. The final thickness of an oil slick between the model pack ice was much greater than that in open water. A correlation was found between ice concentration and oil slick thickness. A comparison of our experimental results and field test results reported by Buist and Bjerkelund (1986) showed that the magnitude relation of oil slick thickness responds to the ice concentration was consistent.

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REFERENCES


