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Cold Regions Science and Technology 38 (2004) 103–116
cold regions science and technology
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Laboratory experiments on oil spreading in broken ice

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Received 29 January 2002; received in revised form 6 October 2003; accepted 6 October 2003

Abstract

In December 2000, laboratory tests were conducted at Hamburgische Schiffbau Versuchsanstalt (HSVA) to investigate the process of oil spreading in cold waters with broken ice. A total of 20 tests was carried out. In each of them, oil was poured on the water surface. Oil spreading and floe motion were closely monitored by video cameras and the pictures were analysed to find how different parameters influence the oil spreading. The following parameters were varied: floe motion, ice concentration, slush concentration and oil type. It was found that spreading rates decreased for increasing ice concentrations, but the effect was small for ice concentrations below 20–30%. The presence of slush strongly reduced the spreading, so that the effect from varying the ice concentrations was reduced. Increased motion in the ice cover resulted in increased spreading rates, and this effect was especially pronounced in the presence of slush.

Keywords: Oil spills; Sea ice; Marginal ice zone; Experimental studies; Small scale tests

1. Introduction

During the last decades, there has been an increased level of human activities in the Arctic. In some waters, year-round navigation takes place and possibilities for oil and gas production are being considered. The latest example is the development of the Snohvit gas field in the Barents Sea, operated by Statoil (2003). As the level of activity increases, there is an increased risk for marine spills of oil in the region. This can be due to ship wreckage, either bunker fuel or oil transported by tanker, or a blow-out at an offshore installation. Rupture of pipelines can also cause oil spills or gas. In case of a spill, it is very important to be able to predict the behaviour of a spill, both changes in chemical and physical properties as well as the location of the spill. This knowledge aids decision making regarding recovery or other means of response. For open water, considerable work has been done and much knowledge is gained.

In the Arctic region, the presence of ice complicates the situation. Models developed for weathering, spreading and drift in open water conditions are in general not suitable. Different scenarios of a spill can create totally different situations. An underwater blow-out under a solid ice cover may cause the oil to spread beneath the ice cover. Alternatively, the plume of oil or gas may break the ice cover and create a scenario featuring broken ice and oil. However, this area can be surrounded by a solid ice cover, acting as a boom to collect the oil and prevent further

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doi:10.1016/j.coldregions.2003.10.004

spreading. An underwater blow-out in a broken ice cover can create the same broken ice and oil situation, but with no solid ice cover to restrict the spreading. Oil can be found in cavities under each floe as well as between the floes. For a surface spill, the oil is initially located between the floes. It may however enter beneath the floes or the floes may be flooded with oil due to dynamic conditions in the ice cover.

This paper focuses on the location and geometry of a surface spill in broken ice. Observations of such spills can be arranged in three categories. First, there is spill of opportunity. This is when an accidental spill takes place and it is possible to observe the incident, which of course is the truly realistic scenario. From a researcher's point of view, there is often lack of information, due to the fact that there was no time to plan the acquisition of data. Equipment and personnel to measure relevant factors as wind or current are usually not available, at least in the initial phase, and a deeper understanding of the working mechanisms can be hard to obtain. There has been several incidents with oil spills from vessels at arctic locations. The Exxon Valdez incident in 1989 in Prince William Sound, Alaska is perhaps the best known. Partly, a field experiment can provide the same realistic situation and gives the researchers time to prepare and plan which parameters they want to monitor. Among others, Buist and Bjerkelund (1986) and Vefsnmo and Johannessen (1994) report field experiments on oil spreading conducted in a broken ice environment. Laboratory tests are suitable for studies of separate or a limited number of factors and their effects. One should always have in mind that scaling effects occur and that absent factors can be more important than expected.

Research on different aspects of oil spill in ice have been carried out during the last three decades. Fingas (1992) gives a thorough summary of existing literature until the start of the 1990s. This summary is based on the report of D.F. Dickins and Associates et al. (1992). Reed et al. (1999) present a review on approaches for oil spill modelling in general during the 1990s. They conclude that the limited ability to model the ice behaviour at a small scale is a key problem for improving the existing models for oil–ice interaction. At present, the models remain highly parameterised and lack dynamic reliability.

During the last two decades, the granular approach has been used as one method to model the ice cover. A model has been developed by Hopkins (1993, 1996, 1999). Each ice floe is described as a separate object interacting with the others, an approach which is especially suitable for the marginal ice zone (MIZ). According to Wadhams (1986), this is the part of the ice cover that is close enough to the open ocean boundary to be affected by its presence, which means that the ice cover is broken into separate floes. As the knowledge of the physical processes governing the ice dynamic behaviour increases, the models offer a detailed description of the dynamic behaviour of the ice. Again, this provides a detailed framework for the spreading and drift of an oil spill inside broken ice.

The tests that have been carried out are suitable for validating an oil spill model. This paper will however only describe the tests and the results. Elsewhere, the results will be compared with simulations from an oil spill model that has been developed and coupled to a discrete element ice model. Refer to Gjøsteen (2001) for a description of the oil model and Hopkins (1996) for a description of the ice model.

Detailed observations of floe geometries and location have been carried out along with measurements of the corresponding oil spreading. This provides data to compare the scenario with simulations in a very detailed manner. It has not been possible to obtain sufficient details to carry out such a validation from tests that have been conducted earlier.

The ice cover is artificially agitated by pulling one of the floes in the tests. Similar scenarios may occur in nature when a dynamic ice cover interferes with, e.g., a fixed structure, a platform, a grounded stamucha or other obstacles. For a reference system on the moving ice cover, the structure will be a moving object.

2. Tests

A total of 20 tests was carried out, the first 3 to be considered as test runs. The procedure of oil injection as well as the amount of oil used were adjusted during the test runs.

As mentioned, the tests were designed to obtain a set of data suitable to validate and improve an oil spill model for broken ice. The most important parameters to monitor at all times were floe positions and the area of the oil spill. It was decided to study the effect of the following parameters: type of oil, ice concentration, amount of slush between the floes and the rate of motion in the ice cover.

In short, each test started as oil was released on the surface in the center of the test area. Shortly after the release, the ice floes were forced into motion. Spreading of the oil as well as the floe motion was recorded in detail by use of video cameras.

2.1. Description of the test basin

The basin is shown in Fig. 1 and the basic dimensions of the basin are given in Fig. 2. As indicated in the figures, the area where the tests were carried out was a 4.5 × 6-m section close to the melting basin. A length of only 4.5 m instead of the planned 6 m was chosen, as this was the maximum area the cameras were able to cover. The section was separated from the rest of the tank by mobile wooden booms. Virgin ice was stored at the left-hand side of the test and, at the right-hand side, the contaminated ice was kept before it was transferred to the melt basin.

As one sheet of ice provided enough ice for several runs, only two sheets were used for the whole set of tests. Each of them was frozen by seeding and kept for about 5 days. The thickness of the ice was about 5–6 cm and the salinity of the water was 3.84%.

Fig. 1. The test basin seen from the melt basin end. The ceiling was about 2.5 m above the ice cover.

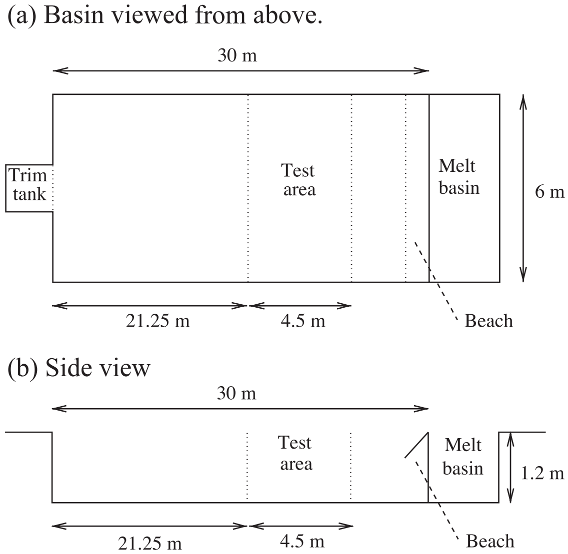


Fig. 2. Dimensions of the test basin.

2.2. Description of tests

The ice floes were convex polygons cut manually by use of a saw, see Fig. 3. Most of them had six corners and a diameter of about 0.5–1 m. Each floe was marked with two white paper markers, each marker about 10 by 15 cm big, see Fig. 4. The marking allows more or less automatic determination of floe positions from the videos. A sufficient number of floes were herded into the test area, distributed evenly and finally brought to rest. In some tests, a considerable layer of slush covered the open leads

Fig. 3. The floes were cut manually by use of saw.

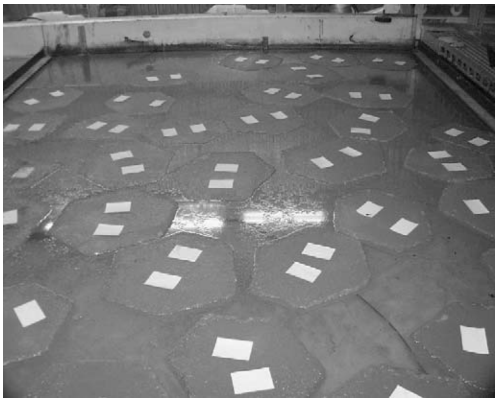


Fig. 4. Each floe was marked with two white markers.

between the floes, in others the amount of slush was minimised. The thickness of the slush layer was measured before the test started. In this situation, the slush was more or less evenly distributed within the test area.

A test started when oil was poured through a pipe having its outlet in the center of the test area, as shown in Fig. 5. Time of injection was a half to 1 min for most of the tests. An amount of 11.0 l of oil was used for most tests and the remains in the buckets and pipe were measured to obtain a more accurate estimate for the volume of the oil spill. Initially, the spreading was driven mainly by gravity and possibly by a small horizontal momentum introduced in the injection procedure.

A short time after the injection was completed, the ice cover was brought into motion by pulling one of the floes along the sides of the test area in a clockwise, circular motion. This floe was manoeuvred manually by two persons, using two ropes attached to the floe, as shown in Fig. 6.

The test was completed when the test area was more or less covered with oil, or in some cases when no change of importance took place.

2.3. Data acquisition and analysis

Four cameras (black and white) were mounted on a frame above the basin, looking straight downwards. Each of them covered one quarter on the test area, overlapping each other slightly. These four cameras provided the primary source of information. In addition, an underwater camera covered the initial spill location and one camera was positioned at the corner of the test section to observe most of the test area from an oblique angle. See Fig. 7 for illustration. The oblique-looking and the underwater camera were both intended to supply us with a qualitative impression of the tests. This could be useful during the process of analysing the tests.

Videos from the overlooking cameras carried all the quantitative information on motion of the floes as well as spreading and movement of the oil. Knowledge of the relationship between lengths in the picture and real lengths, in other words the scale of the picture, is essential. It is also essential that an object has the same dimensions regardless of its position in the picture.

It turned out that the overlooking cameras distorted the pictures to a relatively large degree. This called for

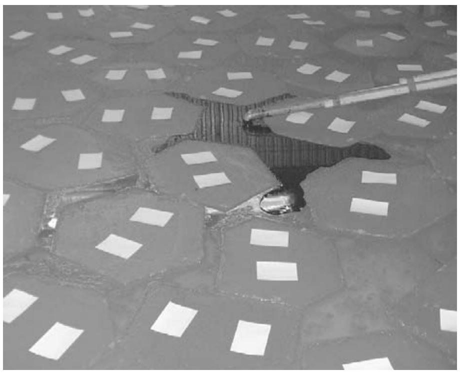


Fig. 5. Oil is injected at the center of the test area through a pipe.

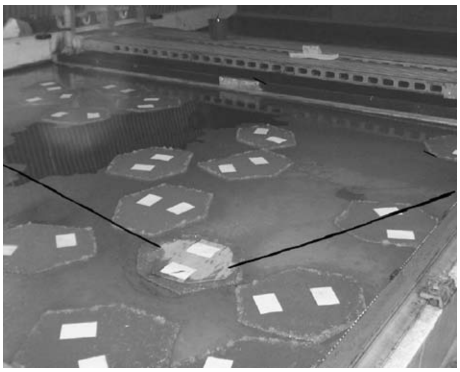
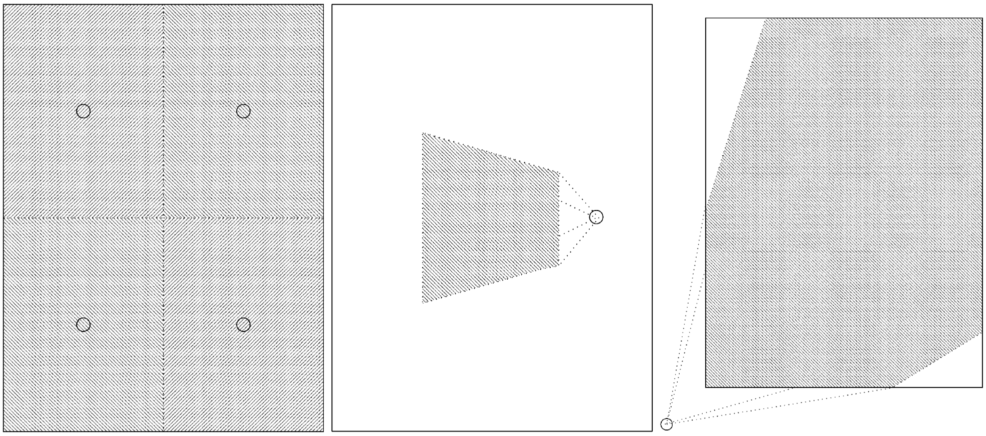


Fig. 6. Motion was created by pulling the two ropes attached to one of the floes.



(a) Coverage of over-looking camers (b) Coverage of under-water camera (c) Coverage of side-looking camera

Fig. 7. Camera positions and their aerial coverage of the test section.

a correction of the recorded images. It was possible to do this by using a grid with known dimensions, see Fig. 8. The grid was placed on the water surface and recorded with the cameras. This image was manipulated to bring the grid into its correct dimensions. The same procedure was used for the other pictures. After correcting each of the four camera images, they were digitally glued together to compose one image showing the complete test area. By using series of such completed pictures, it was possible to track the position of the markers, which in turn gave the motion of the floes. Size and geometry of the oil spill could be determined at any time using the same pictures. An estimate of the spatial uncertainties in the final image is 3 cm. For a detailed description on how the images were built and analysed, refer to Gjøsteen and Løset (in press).

2.4. Test parameters

In Table 1, the tests are grouped according to ice concentration, slush and floe motion. All relevant parameters can be found in Table 3 for each of the tests. In addition, Table 2 gives the important param-

Fig. 8. Grid used to correct the images. The outer dimensions for the wooden frame are 1.5 × 3 m and the squares are 15 × 15 cm.

Table 1
Overview of conducted tests

	Ice concentration (%)	No energy	Low energy	High energy
Open water	0	A17		
between	25	A03	A15, B15, C15	A11
floes	50	A02	A07, B07, C07	A06
	65		A14	
	75	A01		
Slush	0	A18		
between	25		A16	A12
floes	50		A13, B13, C13	A09

The identity of a test is given by a letter indicating type of oil in addition to a number. Type A means IFO-30, B is IFO-30 emulsion mixed with a varying amount of Marine Diesel and C is IFO-30 with 20% Marine Diesel.

Table 2
Parameters for oil samples

Sample ID	Water content (vol.%)	Density (g/ml)	Surface tension, oil/sea water (mN/m)	Surface tension, oil/air (mN/m)	At 10 s^{-1} (mPa s)	At 100 s^{-1} (mPa s)	At 1000 s^{-1} (mPa s)	At 10 s^{-1} (mPa s)	At 100 s^{-1} (mPa s)	At 1000 s^{-1} (mPa s)
					Viscosity at 0 °C			Viscosity at 5 °C		
A	0.2	0.93863	23.2	21.7	822	786	687	431	437	414
B13	1.4	0.93324	19.2	23.1	20800	4090	1280	9920	2310	823
B07	1.7	0.92022	20.5	23.9	10500	2190	634	4490	1020	400
B15	0.5	0.88862	19.9	22.9	259	159	107	122	86	70
C	0.4	0.92241	17.0	22.5	909	591	395	352	284	235

Sample A is the IFO 30 bunker oil used for all Axx runs. Samples B13, B07 and B15 are IFO 30 emulsions mixed with increasing amount of Marine Diesel and used for corresponding runs, and sample C are IFO 30 with Marine Diesel used for the Cxx runs.

eters for the oil types that were used. The oil samples have been analysed at SINTEF Applied Chemistry. Note that the oils were of German origin and may have other specifications in other countries. For a Newtonian fluid, there is a linear relationship between the applied shear stress and the rate of deformation.

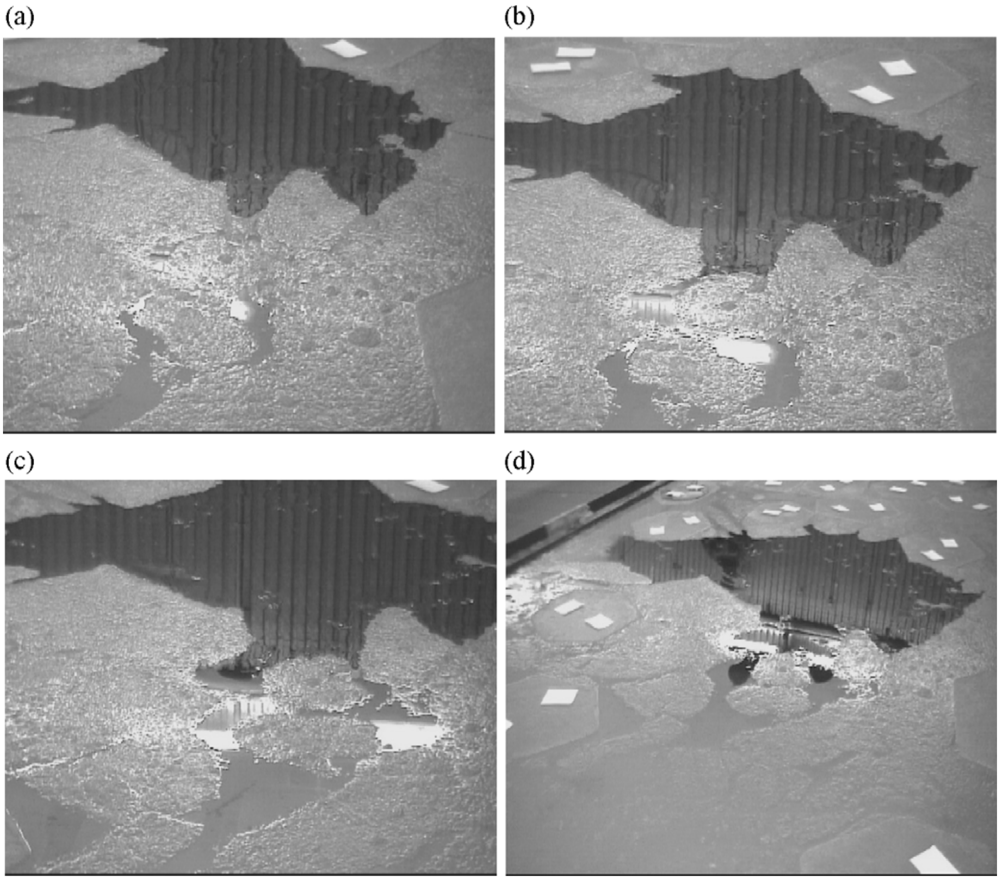


Fig. 9. Oil is spreading into open waters as there are leads in the slush cover. To get an indication of the scale, compare to the quarter of an A4 page white markers (test A16).

This means that the viscosity is independent of shear rate. However, waxy or very viscous oils can exhibit non-Newtonian behaviour, which means that the viscosity vary with the shear rate. That effect is observed for the oil types that have been used in the tests.

Three levels of energy input have been defined for the tests. They are high energy, low energy and no energy and correspond to the level of agitation of the ice floes.

3. Results

3.1. General observations

It is observed that the presence of slush strongly restrict the spreading of oil. When floes diverge, and in that manner create leads free of slush, the oil tends to entrain into these areas very quickly. See Fig. 9 for illustration. If the field converges again, and the slush-free areas are closed, the oil seems to be pushed on top of the slush. For the tests with considerable amounts of slush, the oil spreading was slow at the beginning, as the slush was evenly distributed throughout the area. After a while, the motion created slush-free zones and the spreading rate increased.

The oil did in general not spread on top of the slush cover, but rather seemed to push the slush aside in the initial phase when the oil thickness was large. As the ability to push decreased with oil thickness, the slush turned into a physical obstacle to the oil. The boundaries between oil and slush were fairly straight. Further spreading was then governed by the motion of the ice cover.

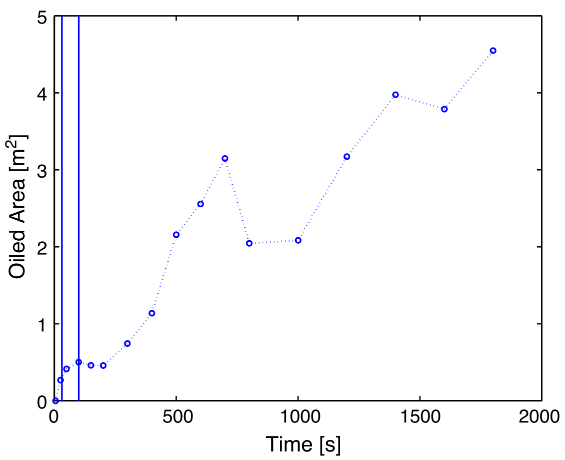


Fig. 10. The oiled area versus time for test A13. The first vertical line indicates the time when all oil is entered in the test area. The other line marks the time when the ice cover is forced into motion.

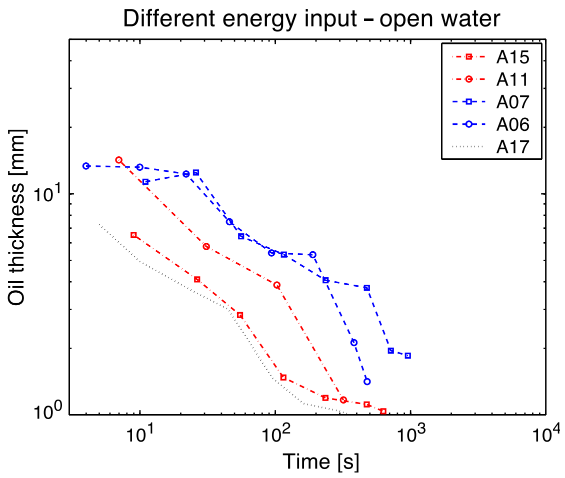


Fig. 11. Oil thickness versus time for tests without slush. Two pairs of tests are displayed in addition to test A17, which has zero ice concentration. The pairs are plotted with the same type of lines and square markers indicate the lowest energy input. Refer to Table 3 for detailed descriptions of the different tests.

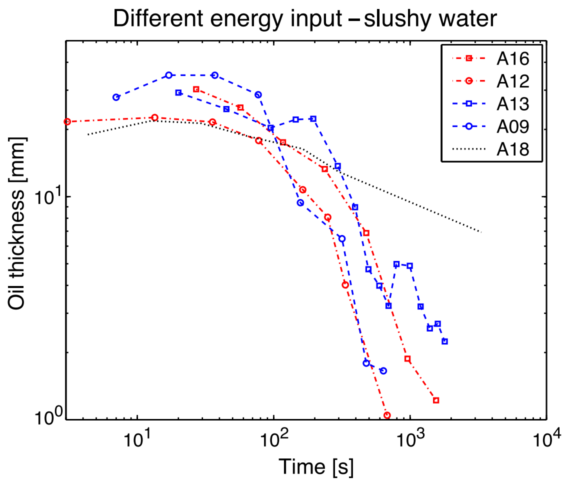


Fig. 12. Oil thickness versus time for tests with slush. Two pairs of tests are displayed in addition to test A18, which has zero ice concentration. The pairs are plotted with the same type of lines and square markers indicate the lowest energy input. Refer to Table 3 for detailed descriptions of the different tests.

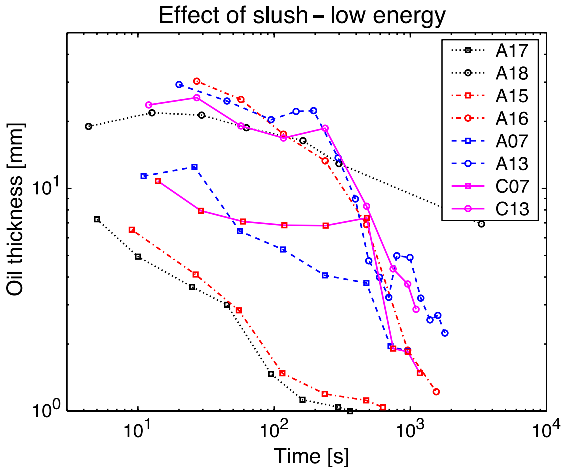


Fig. 13. Oil thickness versus time for tests with low energy input. Three pairs of tests are displayed in addition to tests A17/A18, which has zero energy input. The pairs are plotted with the same type of lines and square markers indicate the condition with no slush. Refer to Table 3 for detailed descriptions of the different tests.

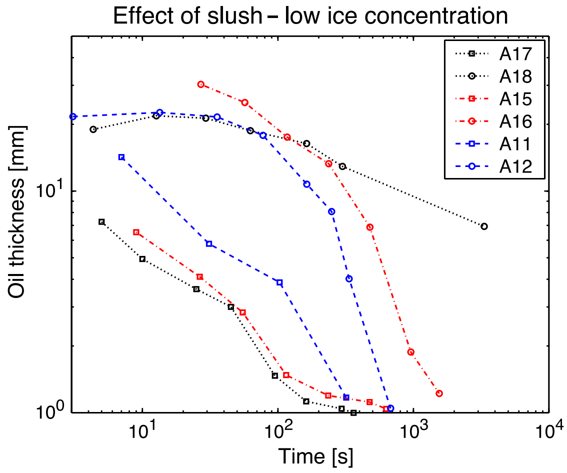


Fig. 15. Oil thickness versus time for tests with low ice concentration. Two pairs of tests are displayed in addition to tests A17/A18, which has zero ice concentration. The pairs are plotted with the same type of lines and square markers indicate the condition with no slush. Refer to Table 3 for detailed descriptions of the different tests.

In test A13, it is observed that the area of the oil spill decreased at one point in time. This is probably because the ice field locally became denser in the area of the spill. See Fig. 10 for illustration. After some time, the spreading continued as normal. It is reasonable to believe that this effect could be observed due to the presence of slush in this test. In the tests with open water between the floes, the oil

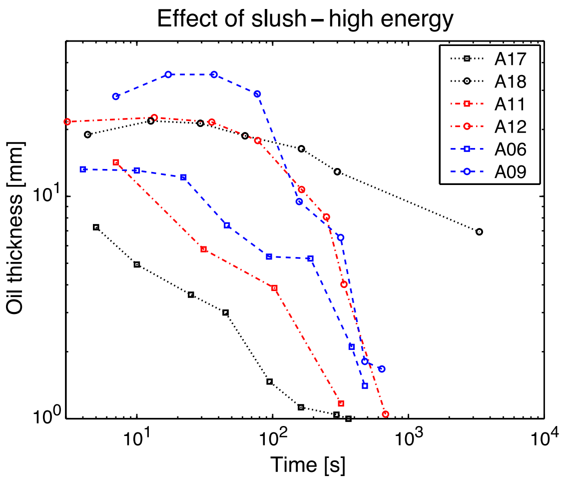


Fig. 14. Oil thickness versus time for tests with high energy input. Two pairs of tests are displayed in addition to tests A17/A18, which has zero energy input. The pairs are plotted with the same type of lines and square markers indicate the condition with no slush. Refer to Table 3 for detailed descriptions of the different tests.

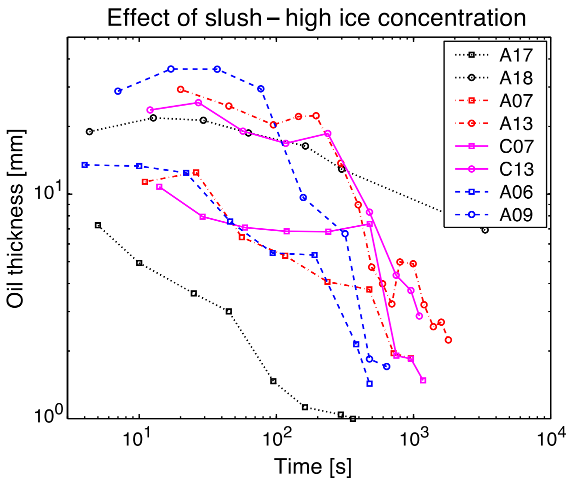


Fig. 16. Oil thickness versus time for tests with high ice concentration. Three pairs of tests are displayed in addition to tests A17/A18, which has zero ice concentration. The pairs are plotted with the same type of lines and square markers indicate the condition with no slush. Refer to Table 3 for detailed descriptions of the different tests.

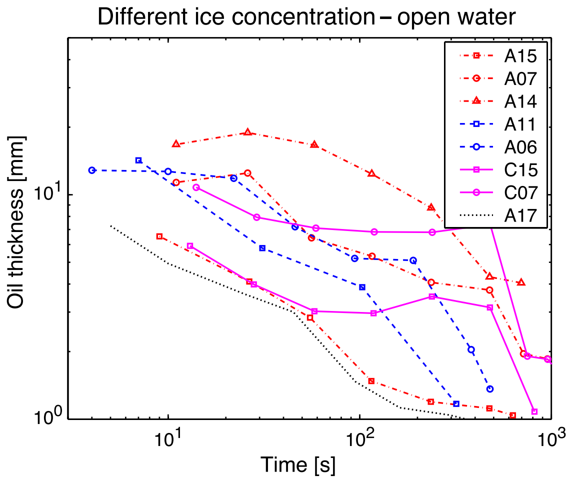


Fig. 17. Oil thickness versus time for tests with no slush. Three groups of tests are displayed in addition to test A17, which has zero ice concentration. The groups are plotted with the same type of lines, and square markers indicate the lowest ice concentration, circular the medium concentration and triangular markers indicate the highest ice concentration. Refer to Table 3 for detailed descriptions of the different tests.

would quickly find a lead to meander through if the field is compacted around the spill. As there is some uncertainties in the observations of spill area and the

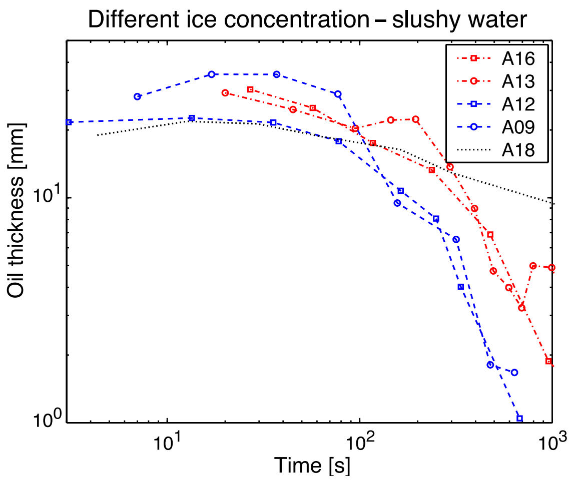


Fig. 18. Oil thickness versus time for tests with slush. Two groups of tests are displayed in addition to test A18, which has zero ice concentration. The groups are plotted with the same type of lines, and square markers indicate the lowest ice concentration, circular the medium concentration and triangular markers indicate the highest ice concentration. Refer to Table 3 for detailed descriptions of the different tests.

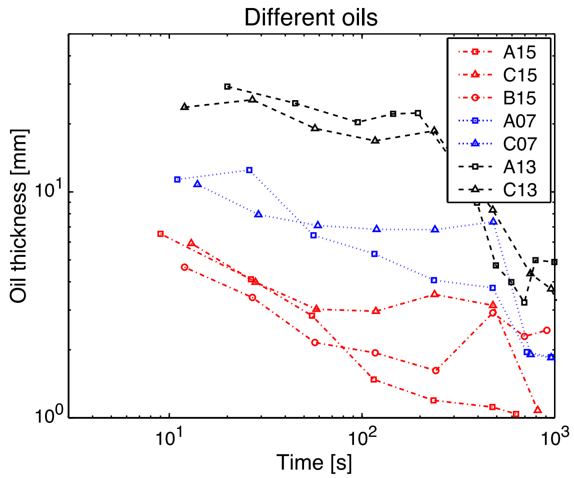


Fig. 19. Oil thickness versus time for tests with different oils. Three groups of tests are displayed. The groups are plotted with the same type of lines. Refer to Table 3 for detailed descriptions of the different tests.

test area is small, one can not expect to observe all these details.

3.2. Oil spreading related to ice characteristics

The oil spreading versus time is presented in Figs. 11–19. Each of the figures shows the average oil thickness versus time. The oil thickness is calculated based on the observed oiled area and the volume of oil present in the system. Time is defined to be zero when the oil injection starts. It has been assumed that the injection rate is constant, and this assumption is used to calculate the oil volume present in the system during the spill time.

4. Discussion

The scenarios that have been created indoor in these experiments have parallels in nature. As a dynamic ice cover meets a fixed structure, from the ice cover's system of reference, it will look as if the object was moving in the field. Examples of such a structure could be a grounded stamucha, a moored ship or a platform.

If the details regarding the ice motion are left out and an energy point of view is taken, there are other possible ways of creating motion. Waves entering an ice cover are attenuated, and during this process they transfer energy to motion in the ice cover. Shen and Squire (1998) give a clear description of the processes, as they investigate the phenomena for a field of pancake ice. They indicate how much of the wave energy that is absorbed in the water column, transformed into motion and absorbed in floe collisions, scattered between the floes or absorbed in floe deformation.

Similar energy parameters are commonly used in other related fields. The formation of water in oil emulsions depends on the energy in a system, as well as the effect one can obtain when a dispersant agent is applied on an oil spill.

4.1. Some remarks

- The slush was evenly distributed at the beginning of the experiments, but it tended to gather in the corners and sides after the floes started moving.
- The oil spills had somewhat different initial temperatures from one experiment to another. About 5–10 °C in general.
- When the oil was injected, it sometimes moved some of the floes in the center of the test area. This occurred especially when the ice concentration was low and for experiments without slush.
- When the oil was injected, it had a small impulse in direction of the melt basin. This is due to the geometry of the input pipe.
- It was discovered during analysis of the pictures that the position of the four over-looking cameras had been changed without the authors' knowledge. It appears that the frame they were mounted on had been lifted slightly, and this causes an increased uncertainty in the B- and C-tests. It is reasonable to suggest that the uncertainty has been doubled.

4.2. Initial temperature of the oil

Let $T(t,x)$ be the vertical temperature profile inside the oil and let the x-axis be directed downwards, starting at the surface of the oil. The equation

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial^2 x} \tag{1}$$

is solved, where κ is the thermal diffusivity, and initial conditions are

$$T(0,x) = T_{\text{init}} \qquad \text{for } x \in [0,L] \tag{2}$$

and boundary conditions are

$$T(t,0) = T_{\text{air}} \text{ and } T(t,L) = T_{\text{water}}.$$

This can be the description of a layer of oil with thickness L and initial temperature T_{init}. Below the oil, $x>L$, is water with temperature T_{water}, and above is air with temperature T_{air}. Both in water and air the temperature is taken to be constant.

If the following parameters are used: $L=10$ mm, $T_{\text{water}}=-2$ °C, $T_{\text{air}}=-7$ °C, $T_{\text{init}}=5$ °C and 10 °C and $\kappa=10\ 10^{-8}$ m^2/s, the temperature profile inside the oil after 2 min would be as shown in Fig. 20. The settings are representative for the experiments. This indicates that the differences in initial temperatures of the spills mainly affect the very beginning of the experiments, namely the spill time. However, one should have in mind that for the experiments with slow spreading rate, the viscosity of the oil will tend to be lower than for corresponding spills that spread faster. The differences in viscosity will decrease with time.

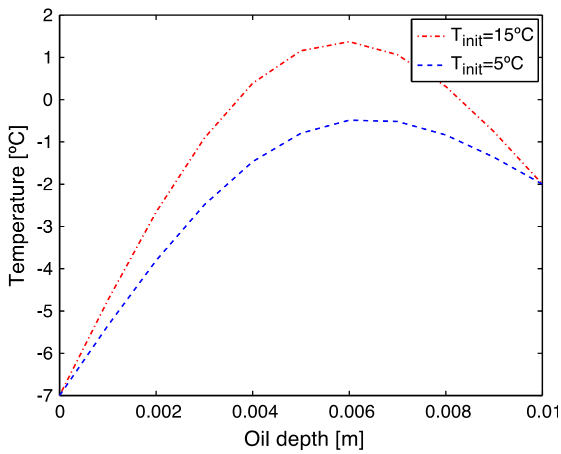


Fig. 20. Temperature profile after 2 min inside a 10-mm-thick oil slick, assuming initial oil temperature of 5 and 10 °C, a water temperature of −2 °C and an air temperature of −7 °C.

Table 3
The parameters for the tests. Some of them are observed and some are calculated

Test ID	Observed parameters								Calculated parameters				
	Water temperature (°C)	Air temperature (°C)	Spill volume (l)	Spill time (s)	Slush thickness (mm)	Ice thickness (mm)	Ice concentration (%)	Floe motion (H/L/−)	Ice concentration (%)	Effect, P_1 (W/m^2)	Effect, P_2 (W/m^2)	Average floe size (m^2)	Number of floes
A01	−1	−7	6.0	–	0	54	75	–					
A02	−1	−4	12.2	–	0	57	50	–					
A03	−1	−4	10.5	34	0	57	25	–					
A06	−2	−6.5	10.2	30	0	60	50	H	47	$4.0 \cdot 10^{-3}$	$9.7 \cdot 10^{-2}$	0.30	40
A07	−2	−6.5	10.4	28	0	53	50	L	43	$3.4 \cdot 10^{-3}$	$5.0 \cdot 10^{-3}$	0.30	36
A09	−2	−6.5	10.2	29	20	60	50	H	44	$2.5 \cdot 10^{-3}$	$1.6 \cdot 10^{-2}$	0.31	36
A11	−2	−6.5	10.0	36	0	60	25	H	27	$6.5 \cdot 10^{-3}$	$9.2 \cdot 10^{-2}$	0.27	24
A12	−2	−2	10.3	35	15	60	25	H	25	$7.0 \cdot 10^{-4}$	$5.3 \cdot 10^{-2}$	0.27	24
A13	−2	−7	10.2	26	20	53	50	L	45	$7.1 \cdot 10^{-5}$	$7.4 \cdot 10^{-4}$	0.32	35
A14	−2	−8	9.8	57	3	38	65	L	63	$1.0 \cdot 10^{-3}$	$4.2 \cdot 10^{-3}$	0.26	63
A15	−2	−6	10.0	45	0	48	25	L	25	$6.1 \cdot 10^{-4}$	$3.8 \cdot 10^{-3}$	0.32	20
A16	−2	−7	10.1	44	22	50	25	L	28	$4.0 \cdot 10^{-5}$	$5.1 \cdot 10^{-4}$	0.31	23
A17	−2	−7	10.2	47	0	0	0	–	–	–	–	–	0
A18	−2	−7	10.5	23	25	0	0	–	–	–	–	–	0
B07	−2.5	−6.5	10.0	69	0	53	50	L					
B13	−2.5	−7.5	9.7	98	35	53	50	L					
B15	−3.4	−6	10.6	22	0	44	25	L	30	$1.1 \cdot 10^{-3}$	$4.5 \cdot 10^{-3}$	0.25	30
C07	−2.5	−6.5	10.5	22	0	53	50	L	44	$5.2 \cdot 10^{-4}$	$4.4 \cdot 10^{-3}$	0.25	45
C13	−2.4	−6.5	10.5	22	30	48	50	L	46	$5.2 \cdot 10^{-4}$	$3.5 \cdot 10^{-3}$	0.22	54
C15	−2.4	−6	10.6	21	0	48	25	L	30	$2.6 \cdot 10^{-4}$	$3.1 \cdot 10^{-3}$	0.25	30

For motion of the ice cover: H = high and L = low. Note that A01, A02 and A03 are the test runs, and are thus not analysed in detail. Tests B07 and B13 were not successful and are not analysed. The effect is a measure for floe motion, P_1 is before the ice cover is manually agitated and P_2 after agitation has started.

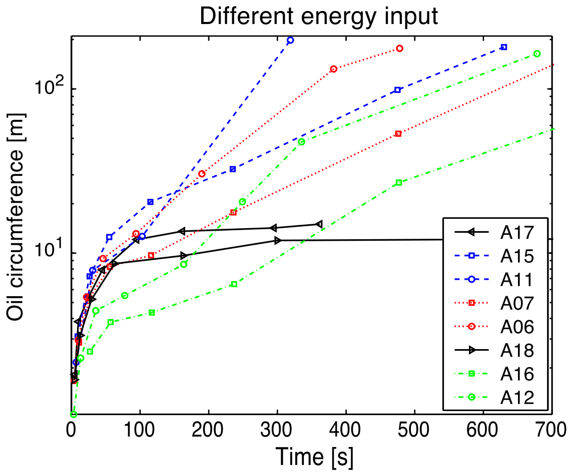


Fig. 21. Circumference of some oil spills. The pairs with the same types of lines are similar experiments, but with different effect P_2.

4.3. About the floe motion

Two columns regarding effect are given in Table 3. These parameters describe the rotational and translatorial motion of the complete ice cover and can be taken as a measure of the level of motion in the ice cover. There will be some motion amongst the floes even before agitation is started, as the spreading oil pushes the floes. It can be observed in Table 3 that the initial effect P_1 seems to be connected to the concentration of slush. Due to the slush, the oil is thicker and exercises a greater push on the floes. However, the slush makes the configuration of floes slightly more consolidated and the last effect is obviously more important in this setting.

For the fast motion experiments, it is seen that the effect P_2 is of magnitude 10^{-2} and, for the slow motion experiments, the magnitude of the effect is 10^{-3}. It is not surprising that there are differences inside the groups, as the only means of determining the motion during the experiments was visual observations and the only way of adjusting the motion was by manually changing the pull in the two ropes. The calculated effects do however confirm that there are two distinct groups of tests with different level of ice floe motion.

4.4. Relevance of the work

As mentioned in Section 1, the experiments that have been carried out are suitable for validating an oil spread model based on a discrete element model for broken ice. There is much work to be done before one can expect to have models that can reliably predict the ice motion in large areas and at a small scale. For this reason, it could be argued that it is a waste of time to study the oil–ice interaction at such a detailed level as is done in these tests. The authors' opinion is however that the knowledge-gained knowledge will be useful in the future.

There are also cases where a detailed oil spreading model can be useful as soon as it is operational. A loading turret, an offshore installation or a fairway of ships are all examples of geographic locations that can be subjected to an increased risk of oil spillage. At such predefined locations, it is feasible to closely monitor the ice conditions, and create reliable models. Detailed knowledge of oil–ice interaction leads to increased preparedness in case of a spill. Predictions

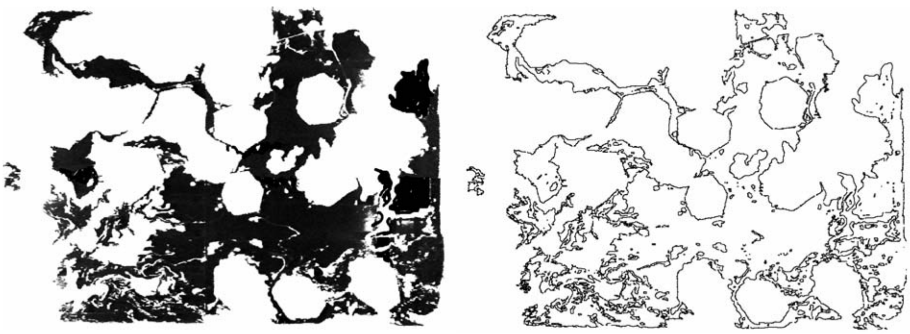


Fig. 22. Spill A11 and its boundaries at the end of the experiment.

can be carried out when a spill occur, or investigations can be made to obtain knowledge of a probable scenario in advance.

Fig. 21 shows the length of the circumference, or boundary between oil and water/ice, for some of the experimental oil spills. See Fig. 22 for an example of the boundary of an oil spill. Such factors can be indicators for the environmental damages a spill can cause. A relevant question concerning an oil spill close to a structure is whether it can be burned when it has travelled a safe distance from the structure. One crucial factor in this setting is sufficient thickness of oil. According to Guénette (1997), this would typically be about 1–3 mm. As it appears, see Section 3.1, the oil thickness can increase for special ice conditions when the ice cover is compressed.

5. Conclusions

A total of 20 tests have been carried out to investigate the process of oil spreading in cold waters in a broken ice cover. The effects of floe motion, ice concentration, slush concentration and oil type have been studied.

The spatial uncertainty of about 3 cm ensures the results to be of acceptable quality. Parameters that are needed to compare the results with an oil spreading model have been measured. The model must accept the motion of polygonal ice floes as a physical boundary for the process of oil spreading in cold waters. Data from this experiment will serve as a first validation of an oil spreading model, but for further development and validation, additional basin tests must be carried out. When the model is developed to a level where it can be trusted on a small scale, field tests should be carried out to ensure its performance on a larger scale.

- As ice concentration increases, the spreading rate decreases. However, it appears that the effect is rather small until the ice concentration reaches 20–30%. The presence of slush diminishes the effect.
- Increased energy input or floe motion increases the oil spreading. The effect is especially pronounced in the presence of slush. Although motion promotes spreading, it is not enough to balance the decreased spreading due to the presence of the ice floes. Test A17, which has zero ice concentration, shows the most rapid spreading. In the corresponding tests with slush between the floes, it was also observed that the oil spreading under ice cover in motion is larger than that of the zero ice concentration test.
- The main difference between the different oil types is the viscosity. It is reasonable to expect that increased viscosity causes decreased spreading rates. One should have in mind that the initial temperature of the oils are about 5 °C, rapidly decreasing to −2 °C. This will in general increase oil viscosity. As the change in viscosity depends on oil type, one would expect oil A to be more viscous than C in the start, but after some time the situation is the opposite way around. This corresponds well to the results. The oil used in B15 is the less viscous at any time.

Acknowledgements

The authors would like to thank the Hamburg Ship Model Basin (HSVA), especially the ice tank crew headed by Karl-Ulrich Evers, for the hospitality, technical support and professional execution of the test program in the ARCTECLAB. They would also like to thank Per Olav Moslet for additional assistance during the tests. The research activities carried out at the Large Scale Facility ARCTECLAB were granted by the Human Potential and Mobility Programme from the European Union through contract HPRI-CT-199900035. Financial support from Norsk Hydro and The Research Council of Norway is gratefully acknowledged.

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