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Oil Behaviour in Ice-Infested Waters

M.F. Fingas[1] and B.P. Hollebone[2]
[1]Spill Science, Edmonton, Alberta, Canada, E-mail: fingasmerv@shaw.ca
[2]Emergencies Science and Technology Section, Environment Canada, Ottawa, Ontario, Email: bruce.hollebone@ec.gc.ca

ABSTRACT 285466:

The current knowledge of the physical fate and behaviour of crude oil and petroleum products spilled in Arctic situations is reviewed. Oil in and under ice undergoes a variety of processes depending on location and environmental conditions. Modeling of oil in such environments becomes complex by the addition of these processes.

Spreading was evaluated for oil on ice, under ice, in snow, in brash ice, and between blocks of ice. Oil transport under sheet and broken ice are considered, both for sea and river conditions. The movement of oil under the ice may be governed by the undersea roughness as well as the relative velocity of the water with respect to the ice. The effects of oil on a growing ice sheet are examined, both for its effects on ice formation and for the thermal effects of oil inclusions in ice. The migration of oil through ice is examined, focussing primarily on the movement through brine channels. The effects of oil on the surface of ice are considered, with emphasis on the effects of surface pools on ice melt. Similar consideration is given to the effects of oil on snow on the surface of ice.

The quantitative studies of oil in open and dynamic ice conditions are reviewed. Observations of intentional small-scale spills in leads and ice fields are reviewed and compared with observations from real spills. The most common ultimate fate of oil in an ice field is release onto water.

Some of the measurements made in earlier years suffered from the lack of good measurement techniques. Further research is needed to improve the understanding of oil behavior in ice-infested waters.

INTRODUCTION:

Research efforts including field tests and observations, laboratory tests, and numerical studies have been expended to understand the interactions that occur when oil is discharged in cold waters or where ice is present. Research has been conducted using laboratory or test tanks and field experiments. Much has been learned from accidental spills in ice-infested environments. Several studies have combined results from Arctic oil behaviour (Hollebone et al., 2000; Yapa et al., 2006: Sørstrøm et al., 2010: Faksness et al., 2009; Fingas and Hollebone, 2013).

This paper summarizes the studies of oil behaviour in ice environments under headings of the specific ice situation or behavioural mechanism. The behavioural mechanisms will then be summarized. Readers may also examine some of the papers specifically on this topic. (Brandvik and Faksness, 2009; Brandvik et al., 2006; Fingas and Hollebone, 2013).

2. Spreading on ice

Many of the oil spreading models on ice are based on Fay and Hoult's (1971) semi-empirical model of oil spreading on open water. The dynamics of spreading was divided into three successive regimes or phases characterized by opposing forces which dominated each phase. The phases are: gravity-inertia, gravity-viscosity and interfacial tension-viscosity.

Others developed empirical equations based on experimental work. Glaeser and Vance (1971) studied the spreading of hot oil on ice using releases onto ice. The ice surface absorbed the oil to a saturation level of about 25%. Chen (1972) conducted studies in the field using small spills. He found that there was no spreading below -19°C and that warm oil (room temperature) spread rapidly. McMinn (1972) developed spreading equations based on Fay and some empirical work and concluded that gravity is the only important spreading force and radius can be given as a function of time. McMinn and Golden (1973) later revised this relationship. Buist et al. (2009) used the work of McMinn to compare test results. Chen et al. (1974) conducted laboratory experiments on spreading and developed a quasi-empirical equation based partially on Fay. Exact equations from the above discussion on spreading are published in Fingas and Hollebone (2013).

Kawamura et al. (1986) conducted extensive laboratory experiments and some small-scale field experiments on the spreading of oil on ice. Considering all the forces on a slick, Kawamura et al. concluded that the final area of spreading related to a number of parameters including viscosity, density and surface tension but were able to simply to an equation where only initial oil volume and viscosity were necessary to predict slick thickness. Subsequent authors subsequently used these formulae to predict spreading. Buist et al. (2009) used a form of the Kawamura equation to compare to experiments on ice.

Comparison of these forms of spreading has never been done on a rigorous basis. It is obvious that the equations presented by various researchers, will not show identical results because even simple quantities, such as spill amount, have quite different relationships in the different equations. In particular, while Chen *et al.* (1974) concluded that gravity and viscosity were the dominant forces, the work by Kamamura *et al.* showed that oil-ice interfacial tension was also important. Tests showed that the Kawamura work did correspond to field results to some degree (Buist et al., 2009).

3. Spreading on or in snow

Kawamura et al. (1986) extended the oil-on-ice equations to predict the spreading of oil on snow. Ross and Dickins (1987) and Buist et al. (2009) developed and tested an equation to predict the spread of oil in snow using density, viscosity and the porosity of snow as major factors.

4. Spreading under ice

Glaeser and Vance (1971) studied the spreading of oil under ice using several small releases. They found that the oil remained near the site with little spreading and filled nearby undulations under the ice. Keevil and Ramseier (1975) studied the sub-ice behaviour of oil by releasing hot crude oil (> room temperature) under the ice. They found that the oil separated into droplets 0.1 to 0.2 cm in diameter. NORCOR Engineering (1975) studied the behaviour of oil released under a first-year ice sheet in the Beaufort Sea. Upon release, the oil formed small droplets less than 1 cm in diameter and spread to form a thickness of no less than 0.8 cm and up to 20 cm in deep depressions under the ice.

Chen et al. (1976) observed the spreading of oil under a freshwater ice sheet in a small test tank. Greene et al. (1977) studied the spreading and behaviour of oil using an experimental spill of warm (room temperature) crude oil under the ice of a freshwater pond. The oil spread to thicknesses of about 0.5 to 2 cm.

Dome Petroleum Ltd. (1981) studied the behaviour of oil and gas releases (simulated by compressed air) under first-year ice in the Beaufort Sea. The release rate was equivalent to 400 m^3/day of oil (2500 barrels per day) at a gas-to-oil ratio of 200:1. Goodman and coworkers (1987) developed a technique using molding to copy under-ice surface contours and then measure the volume of under-surface ice. Literature values of storage volumes fractions were reported to range from 0.01 to 0.06 (m^3/m^2).

Uzuner and coworkers (1979) studied the movement of oil under a smooth ice sheet in a test flume and developed some equations describing this velocity. Puskas and McBean (1986) studied the movement of oil under ice and developed a theoretical model which was calibrated using a small-scale laboratory flume. Puskas and coworkers (1987) developed the relations further and developed equations for slick thickness based on static fluid equations.

Yapa and Chowdhury (1989) tested an empircal equation and developed a new expression for the final radius of oil spreading under ice. Izumiyama and Konno (2002, 2004) studied the spreading of oil under ice surfaces in a test tank and correlated the data with literature values.

In summary, under quiescent conditions (low currents), the oil will spread upon reaching the under-ice surface under the combined actions of buoyancy, viscous, and surface tension forces. A number of force-balance models have been developed to predict spreading under a smooth ice bottom. However, in practice, sea-ice is characterized by significant under-ice roughness. The oil has been observed to spread progressively, filling the nearest under-ice depressions first before “overflowing” into the next depression. Local ice conditions are much more important to the final oil disposition than microscale spreading behaviour. Comparison of the numerical under-ice spreading models has shown that the results are not comparable. The reason for this is likely that factors such as under-ice roughness, etc. were not considered in the formulation of models.

4.1. Water Stripping Velocity under Ice

When oil is under ice, the droplets of oil will adhere to the upper ice surface and will move after a certain water velocity is attained. This water velocity is sometimes called the stripping velocity or critical velocity. At relatively high currents (i.e., greater than 20 cm/sec as observed in laboratory tests), oil and gas may be stripped from the under-ice depressions. At lower currents, field tests have shown that the oil rising through the water column will be carried downstream until it reaches the under-ice surface, after which it will adhere to the rough skeletal layer of growing ice. Buist et al. (2009) employed the earlier equation of Cox and Schultz (1980) to predict the water stripping velocity.

5. Spreading on water with ice present

Spreading on water with ice present has been the subject of modeling for many years. Historically, there were two rules of thumb - if the ice coverage was less than 30%, the oil movement and spreading would not include the ice and if the ice coverage was greater than 60 to 70%, the oil would drift with the ice (Brandvik et al., 2009: Faksness et al., 2010; Vefsnmo and Johannessen, 1994). The spreading of oil is very much reduced in the presence of ice, often resulting in thicknesses as great as centimetres (Singsaas, et al., 1994). Khelifa summarized the modeling work carried out on oil spreading and transport when ice was present (Khelifa, 2010). An extensive review was given of the Johansen (1989 and Johansen et al., 1995) approach in which correction factors are applied to various current components and states in which the oil is found such as trapped under ice, etc. Sayed and Løset (1993) studied the spreading of oil on water and among brash ice and produced a set of relationships for this. Laboratory testing of oil spreading in brash ice has shown that the ice effectively confines the oil. Gjøsteen (2004) developed a model for spreading in cold waters. Analytical expressions were developed and the results compared to experimental data from the author's own data (Gjøsteen and Løset, 2004). Oil can be seen spreading among pack ice in Figure 1. In this case, much of the oil adsorbs to the frazil ice present.

Figure 1 Oil spreading among pack ice floes. Here, the presence of much frazil ice prevents spreading and adsorbs much of the oil.

6. The effect of gas on oil-under-ice spreading

Purves (1978) studied the spread and behaviour of oil released under saline ice in a test tank along with a 60:1 ratio of gas to oil. Dome Petroleum Ltd. (1981) used compressed air to simulate a gas and oil well blowout under ice. Release of gas resulted in ice fractures and ice heaving. As gas is likely to be released in much greater quantities than oil during a blowout, the area of contamination will be affected significantly if the gas is vented (which can occur if the ice sheet is cracked by the buoyant force of the trapped gas bubbles).

7. Movement through ice

NORCOR Engineering (1975) studied the behaviour of oil released under a first-year ice sheet in the Beaufort Sea. The oil rapidly became encapsulated and remained in place until February and March when it began to migrate through former brine channels to the surface. Martin (1979) studied brine channel formation in the field. When sea ice forms, the surface ice has a saline layer. When the ice warms in spring, the surface salt layer liquefies and drains through the ice, preferentially through column interstitial spaces, leading to the formation of top-to-bottom brine channels.

Dome Petroleum Ltd. (1981) studied the release of oil and air (to simulate gas) under first-year ice in the Beaufort Sea. The oil was encapsulated several days after the experiment. Buist et al. (1983) conducted experiments in which oil and water-in-oil emulsion were placed under first-year ice in the Southern Beaufort Sea. Both the oil and emulsion were encapsulated within 48 hours. The oil migrated to the surface through the brine channels and the emulsion remained as emulsion and appeared on the surface only by ice ablation.

Payne et al. (1990) conducted a series of indoor and outdoor experiments to evaluate the fate and behaviour of oil spills with and under ice. They presented the rise rate velocity of oil through an ice sheet as being largely density and viscosity dependant. Payne et al. (1990) found a rise rate of 0.35 $mm.s^{-1}$ for the experiment they conducted. They noted that Martin (1979) had found a rise rate double this amount. Payne et al. (1990) also calculated a volume flow rate of oil to the surface. Payne et al. (1990) calculated a volumetric flow rate of about 27 $mL.h^{-1}$ for their experiment, which was higher than experimental values.

When the oil and gas are discharged under a growing ice sheet, the oil and gas will be encapsulated in the ice by subsequent growth beneath it. Two aspects of this process need to be considered: 1) the time required for encapsulation to occur, and 2) the effect of the encapsulated oil and gas on subsequent ice growth. During all of the field spills conducted to date under first-year sea-ice, the encapsulated oil was released in the next melt season. The only information relating to the release from under multi-year ice comes from one series of small-scale field spills. These data indicate that the oil will rise quickly to the surface through cracks, but persist for at least two melt seasons on the surface of the ice (as multi-year ice is thicker and the brine channels may be discontinuous or not present).

8. Oil in leads

Cammaert (1980) conducted tank tests on the movement of oil out of leads. It was found that a current of 44 cm/s was required to force oil out of an undulation 1.5 cm deep and a current of 25 cm/s was required to force oil out of an undulation 0.5 cm deep. Buist and coworkers (1987) studied the behaviour of oil in leads using a test tank. Experiments showed that only a fraction of oil was incorporated into newly formed ice. MacNeill and Goodman (1987) studied the effect of lead closure rates on the movement of oil up or under the ice surface. Tests were conducted in an outdoor basin. At lead closure rates at or above 12 cm/s, most of the oil was forced up to the top of the ice. The phenomenon known as ‘lead pumping’ has been postulated as a mechanism to redistribute oil from the water to the ice surface under dynamic conditions. An analysis of lead closure rates in the Beaufort Sea and Lancaster Sound revealed that typical rates were much lower than those required for ‘lead pumping’ (Dickins, 1986). Lead closure is unlikely to serve as a mechanism for distributing oil onto ice surfaces.

9. Absorption to snow (ice)

McMinn (1972) found that snow absorbed 20% oil by volume to yield a mulch that was fairly stable. Buist *et al.* (1987) report a value of 25%. Owens et al. (2005) report on earlier experiments which show an initial absorption of Prudhoe Bay crude of 70% declining exponentially over 6 days to about 40%. Owens noted that diesel fuel showed an initial adsorption of 40% declining to slightly less than 20% over six days. These test results were for fresh snow and would be different for other types. Owens et al (2005) note that few tests have been carried out and little has been done to characterize the snow in any tests carried out.

10. Containment on ice

Deslauriers and coworkers (1977) studied the fate and behaviour of an oil spill incident in Buzzards Bay. Rafted ice led to the formation and containment of oil pools of up to 0.15 m in depth. These pools held approximately 30% of the spilled oil. The ice temporarily prevented oil from reaching nearshore areas.

11. Heating effect of oil on the surface of ice

Glaeser and Vance (1971) studied the heating of oil on ice using releases onto ice. They found that there were large variances, but overall, oil absorbed 30% more heat from the sun than did normal ice. Chen (1972) measured the temperature of oil under snow and found that the oil temperature was 3 to 6°C higher than the air temperature. NORCOR (1975) measured the effect of albedo on the surface and found that the presence of oil may have accelerated the melting of the ice by as much as 1 to 3 weeks. The albedo of the oil test area was as low as half of the surrounding unoiled area. The albedo of the oil is similar to that of melt water pools on the surface. Subsequent field studies (Dome, 1981) did not detect any increase in breakup caused by oiling.

12. Oil under multi-year ice

Comfort and Purves (1980) report on a study of an experimental crude oil spill under multi-year ice in the Canadian high Arctic. Oil was placed under the ice and, when the site was revisited for the first time, most of the oil had migrated to the surface. A revisit to the site five years later showed no oil left, even on the surface. The oil had presumably been absorbed by the snow and carried by winds.

13. Oil in pack ice

The movement of oil in pack-ice conditions is similar to that on open water given that the ice is less than about 50% or 5/10 (Khelifa, 2010). In closer pack ice, however this changes. Ross and Dickins (1987) reported on three experimental spills in pack ice off the eastern coast of Canada. An adjusted Fay model was able to predict the spreading to a large degree and the Kawamura model was less successful.

14. Growth of ice on shorelines and effect on oil retention

Oil fate and behaviour on shorelines can be effect very much by the growth of ice structures on shorelines. If the oil arrives before these structures form, then the oil is trapped until the melting season. If the oil arrives at the shoreline after structures form, then the oil may be kept off the shoreline. Øksenvåg et al. (2009) studied the formation of ice on shorelines in northern Norway noting that the most common types observed were frozen swash and ice foot.

15. Effect of oil on ice properties

NORCOR (1975) measured the effect of five large, oiled under-ice surfaces on the growth rate of ice compared to surrounding areas. They found no measurable effect on ice growth. Chen et al. (1976) studied oil under freshwater ice in a small basin and found that the ice above an oil lens was 2 to 6℃ cooler. This was attributed to the insulating effect of the oil. Greene and coworkers (1977) studied the behaviour of a warm oil (room temperature) release under ice in a freshwater pond. The heat transfer to the water and ice occurred rapidly and did not affect ice growth after a few hours. Martin and coworkers (1977) studied the growth of grease and pancake ice in a test tank. It was found that oil released to the water surface quickly surfaced to the top of the grease ice. The presence of the oil did not affect the ice growth.

Wilson and Mackay (1987) studied the incorporation of oil into grease ice during formation using a small laboratory test tank. It was shown that large amounts of oil are incorporated into the ice as grease ice is formed. Oil in developing and brash ice has been observed to behave in many ways during various spills of opportunity (Fingas, 1993).

Field and laboratory tests of oil behaviour in developing ice (frazil, grease, slush, and pancake ice) are inconclusive. Oil has been observed to surface easily through slush if some agitation is present, but too much agitation can result in incorporation of oil into the ice. Horizontal spreading of oil seems to be hindered by slush, resulting in equilibrium thicknesses greater than that of open water spreading.

CONCLUDING REMARKS:

Oil spills in ice-infested waters undergo complex behaviour and fate processes. There is some understanding of the processes involved in oil interaction with ice. Modeling of this behavior can be carried out at present using many of the concepts presented above. There are gaps and uncertainties in some of the algorithms. Further, many of the equations are not unit consistent and have many differences in inputs. More quantitative research is needed before there is a full capability to predict oil behavior and fate in ice-infested environments. In addition, much of the work is now 30 years or more old and some measurement methods have improved to the extent that older results should be significantly updated.

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