Experimental Study of Behavior of Oil Spills in Ice Conditions

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Abstract. To ensure environmental protection and eliminate oil spills in the Arctic waters, it is necessary to understand the processes and behavior of oil spills in ice conditions. The article presents the results of laboratory studies of behavior of oil spilled in ice conditions, as well as time temperature calculation of the water profile with the formation of ice cover after the oil spill. On the base of the results obtained, recommendations are given on oil spill response by mechanical methods in ice conditions. The distribution of temperatures along the water profile makes it possible to evaluate the state of the frozen oil lens and the possibilities for its extraction.

1. Introduction
At present, development of oil and gas bearing provinces in the Arctic zone of Russia continues in the territories and waters of the northern seas, where huge hydrocarbon reserves are concentrated (80% of Russia's reserves) [1]. Development of oil fields and transportation of petroleum products in difficult climatic conditions impose significant restrictions on work on the Arctic shelf and increase the risks of emergencies, in which oil pollution can occur in both the marine environment and fresh inland water bodies. Despite significant success in the fight against oil spills in the Arctic, the problems of oil spill response (OSR), as well as their behavior in ice-covered reservoirs at low temperatures, have not been adequately studied. Technical feasibility is greatly complicated by severe climatic and geographic conditions that limit the use of existing technologies for gathering oil from the surface of water and oil spill recovery [2-5].

2. Behavior of oil spill in ice conditions
Field, laboratory and theoretical tests and studies of oil behavior in ice conditions have been conducted since the early 1970s, as a result of which a huge knowledge base has been accumulated. Oil in case of an accident (leakage from an oil pipeline or well, an accident during transportation by ships, etc.) may be on the surface of snow and ice, in the ice lead (variants with different ice concentration) or under a solid ice cover, depending on the conditions. When gathering oil in ice conditions, it is necessary to take into account the advantages and disadvantages of the Arctic conditions. For example, the benefits include: increased oil viscosity, hence, greater thickness, smaller area of oil slick and its slow spreading speed that facilitate recovery; the presence of ice and snow prevents the spread and drift of the oil slick; lower evaporation rate; reduced emulsification rate in dense ice; protection of the coast from spills with fast ice. Disadvantages include: complexity or inaccessibility to spilled oil; low efficiency and limited use of some cleaning methods; rapid freezing of oil into the growing ice cover; complexity of detection [6].
2.1. Oil behavior on ice
Propagation of oil on solid ice is equal to its spread on the earth. The speed of propagation depends mainly on the unevenness of the ice surface and the viscosity of the oil. Thus, at low temperatures the propagation velocity tends to slow down and the total area is reduced, so the oil slick on the ice is generally much thicker than the equivalent spots on the water [7, 8].

The laboratory experiment (Figures 1-3) reveals that the oil slick on the surface of water after its freezing in calm conditions does not freeze into ice and accumulates on its surface. Since the ice surface is flat, the oil is easily cleaned mechanically. However, when oil spills on the water surface or ice in actual conditions, the water flow and the relief of the icy surface will influence the final distribution of oil and its availability for removal.

![Figure 1. Oil slick on the water surface.](image1.png)  ![Figure 2. Oil slick on the ice surface after the freezing of water.](image2.png) ![Figure 3. The oil slick is easily removed from the ice surface.](image3.png)

2.2. Oil behavior under ice
The impact of oil and petroleum products on ice is mainly influenced by their density. The density of most heavy oils and petroleum products exceeds the density of ice at a temperature of ~ 0 °C. The difference in density increases as the oil and petroleum products are weathered. In this case, the ice seems to creep onto oil products. At a wind speed of 12 m/s, water flow velocity of 0.5 m/s and an ice thickness of 15-45 cm, such oil and petroleum products are easily pushed under the ice. There the current moves them along the ice bottom face. It has been established that the limiting current velocity is about 0.3 m / s for crude oil to flow under the ice with a significant roughness of the lower surface. That is, oil will not move along the bottom surface of the ice at a water flow velocity below 0.3 m/s, i.e. it will drift along with the ice. If an ice cover is less than 30%, oil can drift independent of the ice. It moves along with ice if ice concentration increases more than 60-70% [9-12].

2.3. Oil encapsulation
In some cases, oil spilled under ice can be completely encapsulated by growing ice for 12-72 hours depending on the season and stay there for a long period of time. Encapsulation proceeds faster in range from 12 to 24 hours under the newly formed ice during the freeze-up; it takes 48 hours in the middle of winter; encapsulation process is unlikely at the end of winter (May) due to slowing or halting of the ice growth rate [8, 13, 14].

Physically, this happens as follows. Ice grows more intensively along the edges of a drop or accumulations of oil, where the thermal conductivity is higher. Then ice sheets begin to form and subsequently, they merge into the ice dome, as a result of which the oil is frozen into ice [15].

Traditional technology for small oil spills involves the use of heavy equipment to transport cut contaminated ice to land, followed by melting and removing oil or breaking up solid ice into pieces and washing them in special mounts [16-18].

It has been established that drops of petroleum products under ice in the presence of water do not have direct contact with it. The action of the ice surface on the petroleum product lens proceeds
through the thinnest water layer [15]. Thereby, an experiment of washing-out the frozen oil lens through the hole is accomplished (Figures 4-6).

![Figure 4. Washing-out the frozen oil lenses.](image1)

![Figure 5. Expanded hole to accelerate the process of washing-out.](image2)

![Figure 6. Practically "clean" piece of ice.](image3)

The experiment results reveal that it is possible to substantially simplify the procedure of cleaning ice from frozen oil without its extraction, by outwashing it through a hole drilled in ice, after preliminary pumping the available volume of oil by pump equipment. From the end of December to the spring melting, the ice cover in the coastal regions of the Arctic is quite stable and allows safe delivery of the necessary technical devices and it becomes possible to conduct contingency plans for OSR. The efficiency of the method depends on temperature conditions of the environment, physical properties of oil, particularly, its setting point. The lower the setting point is, the less viscous oil will be in the ice sheet and, accordingly, more accessible for extraction. Crude oil in many fields of the Arctic zone of Russia has a low setting point [19]. For example, oil from some fields in Yakutia has the following setting point, °C:

- Talakanskaya - 48 [20], -50 [according to the IOGP SB RAS];
- Chayandinskaya - 39 [21];
- Irelakhskaya - 38 [22].

In connection with this, in order to assess the state of oil encapsulated in ice, a mathematical calculation of the dynamics of the temperature distribution along the water profile of a fresh water body after oil spillage and its subsequent freezing under a growing ice cover 10 cm thick was accomplished.

### 3. Temperature calculation of oil spill freezing into ice cover

The problem was solved by the finite element method using Dolfin / FEniCS program. Geometry and triangulation of the computational domain was constructed using GMSH program. Visualization of calculation results was performed with the help of ParaView program.

The calculation is based on the average daily air temperatures in Yakutsk in the period from November to January, taking into account the effect of snow cover under static conditions, i.e. the influence of the water flow was not considered. It is assumed that the water temperature at the bottom of the reservoir is 4 °C. Figure 7 demonstrates the calculation results for the end of December with the following climatic parameters and thermophysical properties of oil:

- average daily temperature of ambient air, °C - 44.2;
- thickness of the snow cover at the end of December, cm - 24.0;
- temperature under the snow cover, °C - 13.9;
- heat capacity of oil, kJ/(kg·K) - 2.1;
- thermal conductivity of oil, W/(m·K) - 0.17;
- oil density, kg/m³ - 920.
The obtained calculation of the temperature distribution along the water profile shows that the oil lens frozen in the ice cover is in the temperature range from -13 to -3 °C, despite the very low ambient air temperature (-44.2 °C at the end of December). This is explained by snow cover acting as a thermal insulator and heat coming from the bottom of the reservoir. The temperature of the oil encapsulated in ice increases with the depth of its location in the ice. The calculation also reveals that the growth rate of the ice cover diminishes under the oil lens. Since the thermal conductivity of oil is lower compared to water, heat transfer through the oil is decreased.

4. Conclusion
Contingency plans for OSR in ice conditions differ from the ones in open water due to more complex conditions and a variety of factors to consider, including the oil behavior. Experiments showed that the gathering of spilled oil can be facilitated depending on the ice conditions. When the water freezes, the layer of oil located on its surface turns out to be on the ice surface (in inactive reservoirs) and can be relatively easily gathered. The oil encapsulated in the ice cover can be outwashed through the holes made in it. Temperature calculation on the water profile revealed the capability of using this method, since oil with a low setting point inside the ice will be in a less viscous state and this will facilitate its extraction. Thus, it is possible to remove oil completely by direct pumping and outwashing after detecting its location and delivering the necessary equipment along the ice road.

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