Method Development for Oil Spill Response Under Ice Cover

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Abstract. This article is continuation of earlier work on the study of oil behavior spilled in ice conditions, results of which showed that, depending on ambient conditions and properties of oil, the latter can be in low-viscosity state, which makes it possible to extract it [1]. The paper presents results of field studies and development of method for containing and gathering oil spilled under the ice cover on their basis. Obtained experimental results are confirmed by mathematical model of the freezing process of water body and substantiate the possibility of containing and gathering oil spilled under the ice.

1. Introduction

The most potentially dangerous source of emergency oil spills in water areas in terms of environmental and economic consequences during the exploitation of oil and gas fields are submerged crossings of oil pipelines. Quite often, complicating factors are ice conditions, as well as high rate of spread of spill spot, significant distance of spill sources from locations of emergency services. Elimination of oil spills in ice conditions is complex technical task and often almost impossible due to difficult climatic and geographical conditions and factors [2-5]. At the same time, the main task of emergency services is the fastest response to emergency to minimize damage. In addition, modern legislation imposes stringent requirements for the containment of such spills. According to the Decree of the Government of the Russian Federation of August 21, 2000, No. 613, the time for containment should not exceed 4 hours [6].

2. Method for containment and gathering of oil spills under ice cover

Due to the fact that thermal conductivity of ice exceeds thermal conductivity of snow and water by an order and four times, respectively, authors propose method for creating cavities and guide channels in the ice cover through which oil spilled under the ice will be contained and gathered.

The objective of proposed method for containment and gathering of oil is to ensure simplicity, reduce labor intensity, efficiency, and economy of the process of gathering of accidental oil spill on flowing water bodies in ice conditions. The advantage of proposed method in comparison with similar methods [7, 8] is the lesser impact of oil pollution on a water body since the method for containing and gathering oil acts immediately upon pipeline break and oil leak. All preparatory work is carried out once and in the future is reduced to only periodic control. Containment and diversion of emergency oil under the ice cover of the water body to gathering zone and subsequent removal is carried out using guide channels created in the ice cover across the water flow at an angle to its dynamic axis.
The method is carried out as follows (Figure 1). Snow thermal insulation (2) is created from natural snow cover by clearing the surface of the ice cover (1) of the water body downstream of accidental oil spill site on supposed path of the oil slick. Thus, conditions will be created for an increase in the thickness of the ice cover under the cleared area, and vice versa, for slower freezing under the snow thermal insulation. In addition, depressions (3) are created on the ice surface for deeper ice freezing and the formation of a more pronounced ice channel (5).

The number and shape of ice channels can vary depending on the width of flowing water body (Figure 2).

3. Experiment
Full-scale experiment was carried out in closed stagnant water body to confirm the possibility of using the method in real conditions. Working zone with diameter of 20 m was cleared from the snow cover. In the center of zone, artificial dome shape insulation with height of 1 m and base radius of 3 m was formed with snow cover. At the beginning of the experiment, thickness of ice cover and depth of water body were 0.24 and 1.65 m respectively. Temperature in water body was 2.5 °C, at the border between snow cover and ice –4 °C, ambient air temperature –23.5 °C. Territory of the zone was cleared as it snowed. Also, temperature of ambient air and water, thickness of natural snow cover, density of artificial snow insulation, and wind speed were recorded to build mathematical model during the field experiment.
On the 36th day from the beginning of experiment, changes in the thickness of ice cover under artificially created snow insulation, as well as from the area cleared of snow and under natural snow cover were recorded. Holes were drilled at 6 points to measure ice thickness as it is shown in Figure 3.

![Figure 3. Hole layout and ice thickness.](image)

Obtained data shows that the increase in thickness in the center of isolated part of ice cover was 7 cm (point 1), while thickness of uninsulated part increased by 50 cm (point 4), the difference between them was 43 cm. Air temperature during the experiment dropped below −40 °C.

Height of snow insulation up to 1 m is sufficient to significantly slow down the growth of ice cover during freeze-up.

4. Mathematical model

Mathematical model that allows predicting the process of ice cover formation in enclosed body of water depending on environmental conditions was built to describe full-scale experiment.

The problem was described by heat conduction equation, considering phase transition in axisymmetric form in cylindrical coordinate system; Derichlet’s and Newton’s boundary conditions were set [9].

This problem is Stephen’s problem of freezing water. Phase transition occurs in small temperature range \([T_f - \Delta; T_f + \Delta]\), thereby the enthalpy of phase transition is "smeared" in this interval.

The numerical implementation of the problem was carried out by finite element method based on the FEniCS computational package [10], for construction of geometric mesh and generation of the mesh using the free access program GMSH was used [11], Paraview was used for visualizing obtained results [12].

Geometrical dimensions adopted in the model problem coincide with geometrical dimensions of the full-scale experiment.

Thermophysical characteristics were as follows

|             | Heat capacity, J/(kg·°C) | Density, kg/m³ | Thermal conductivity, W/(m·°C) |
|-------------|--------------------------|----------------|-------------------------------|
| - Ice       | 2027.0                   | 917.5          | 2.25                          |
| - Water     | 4217.6                   | 1000.0         | 0.56                          |

Heat transfer coefficients were calculated by following formulas [13]:

\[
\alpha_k = \frac{1}{\alpha_k} + \frac{h_k^2}{\lambda_k^2},
\]

\[
\alpha_{air} = \begin{cases} 
6.16 + 4.19v_{air}, & 0 < v_{air} \\ 
7.5v_{air}^{0.78}, & 5 < v_{air} < 30.
\end{cases}
\]
where $h_k$, $\lambda_k$ – height and thermal conductivity of snow cover of the $k$-th boundary, $\nu_{air}$ – wind speed. Values $T_{ice}$, $T_w$, $h_k$, and $\nu_{air}$ were recorded by conducting full-scale experiment. Thermal conductivity of snow $\lambda_k$ depends on density $\rho_k$ and was calculated by following expression [14]:

$$\lambda_k = 0.035 + 0.353 \cdot 10^{-3} \rho_k - 0.206 \cdot 10^{-6} \rho_k^2 + 2.62 \cdot 10^{-9} \rho_k^3.$$  

Figure 4. Temperature distribution in water body.

Figure 4 shows calculated data of temperature field distribution in water body after 36-day experiment, white isoline shows lower boundary of ice cover.

Figure 5. Comparison of ice thickness measurements at control points.

Figure 5 shows comparison of ice cover thicknesses at control points obtained by solving the Stefan problem and measured by field experiment. The deviation of calculated results from experimental data is about 4.8%, which confirms the adequacy of mathematical model.

5. Conclusion
Mathematical model for solving the Stefan problem by finite element method to determine change in thickness of ice cover has been developed. This model clearly describes the process of freezing of water bodies without flow. In the future, it is planned to carry out experimental work in conditions close to real in the presence of a flow.

Comparison of natural and computational experiments shows adequacy of developed mathematical model.

Thus, by regulating the thickness of growing ice cover, it is possible to create guide channels in it for diverting and gathering of emergency oil spill.

6. References
[1] Efimov S E, Gerasimov A I and Tikhonov R S Experimental Study of Behavior of Oil Spills in Ice Conditions Published under licence by IOP Publishing Ltd IOP Conference Series: Earth
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