Oil spill response technology for ice-covered waters in the Arctic

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Abstract. A technology for removing oil spills from under the ice, based on the use of the vortex funnel effect, is proposed. A comparative analysis of methods oil pollution removal from under the ice cover is carried out. Models of the processes of separation of the “ice-oil-water” system occurring in the vortex funnel are presented, as well as, based on the experiment, photo illustrations of the stages of formation of the vortex funnel and removal of oil from under-ice. The schemes of deployment and operation of mobile equipment for removing oil spills from under the ice are proposed. It is shown that the proposed approach to liquidation of emergency oil spills in the Arctic can be used to create means and technologies of liquidation of more large-scale disasters of this kind.

1 Introduction

The Arctic, with its enormous reserves of hydrocarbons, the demand for which grows every year, is becoming a hostage to the energy problems of mankind. The stimulating factor for industrial development of the Arctic is also the decrease of ice cover, which facilitates the development of new oil fields and its transportation.

The harsh natural and climatic conditions of the Arctic imply a significantly greater likelihood of occurrence and response to oil spills, although even in more “favorable” areas, such as the Gulf of Mexico, in 2010 it was not possible to prevent an accidental oil spill and promptly eliminate its consequences.

When eliminating oil pollution in the Arctic, it is necessary to take into account the following factors. The main factor complicating the removal of pollution is ice cover. The presence of ice cover, especially thick ice, being a natural obstacle, greatly complicates the detection of oil spills and their elimination. Other factors include harsh climatic conditions, in particular, low air and water temperatures, long polar nights, and remoteness from land.

At the same time, there are many causes of oil spills, which create their own specific features of their detection, localization and removal. Oil spills can occur due to leaks from onshore and offshore wells, accidents on pipelines, oil storage facilities and oil tankers.

Despite the recommendations of various world environmental protection organizations [1], exploration and development of new hydrocarbon deposits in the Arctic region continues. In this regard, ensuring the environmental safety of oil production requires the development of new effective ways to eliminate its accidental spills in the Arctic, especially during the exploitation of sub-ice fields.

2 Analysis of existing methods of oil pollution removal from under the ice

Despite some success in the development of new technologies for oil spill response in the Arctic [2], they are usually not completed, in particular, due to insufficient funding and lack of interest from oil companies.

The main methods for removing oil include such as mechanical technologies for collecting oil, oil combustion, the use of sorbents and dispersants. However, these methods of oil removal have shown some efficiency in open water, but not in the presence of ice cover [3, 4].

At the same time, of all the listed technological directions for removing oil barriers from under the ice, the mechanical methods are the most environmentally safe, which determines the relevance of their application.

However, the disadvantage of many mechanical methods for removing oil pollution is their limited coverage of processing areas or use in flowing water bodies covered with ice. For example, such technical solutions as those listed in the patents, which consist in the use of devices that provide for the for the arrangement of an ice hole, installation of a winch on the ice, placement of an inflatable boom along the contour of a rectangle under the ice, winding it on the winch drum, pulling oil to the ice hole and pumping it [5

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, 6] refer to preventive measures to protect water bodies from oil pollution, which are mounted in advance over possible accident zones, which is extremely costly and not always acceptable.

In real emergency situations, it is difficult to determine in advance the area of the oil spill. Therefore, the requirements for technology and equipment for liquidation of oil spills under the ice cover should provide for the following conditions.

1. Fast detection and response to an emergency
2. Rapid deployment of emergency response tools
3. Preliminary measures for containment of oil spills
4. Localization and reduction of the spill area
5. Pumping the main volume of oil pollution into reservoirs, their transportation and regeneration
6. Elimination of residual pollution.

One of the important tasks, effective elimination of emergency oil spills, is its rapid detection, the most rational use of underwater vehicles [2]. Quite a lot of developments are devoted to the problem of detecting petroleum products [7, 8].

Despite the intensification of oil production in the Arctic regions, mainly in the sea areas of the Arctic Ocean, there are still no sufficiently reliable methods and devices for collecting oil and oil product spills from under the ice cover [1].

Noteworthy is the technology of oil spill response using the idea of drilling wells in ice and installing booms to collect oil from under the ice cover of a reservoir [9]. Technical solutions in this direction provide for the following operations: drilling a well in the ice, installing under the ice cover a hollow shell equipped with an inflatable fence along the contour, pumping air into its cavities, and injecting a working agent into the contact zone of the shell with the polluted area of ice, removing the working agent from under the ice cover, pollutants from the cavities of the shell and the inflatable air barrier, and removing the shelland the inflatable barrier from the well: drilling another well in the ice cover with operations including removing pollutants from under the ice cover. When drilling wells in the ice, the installation of the shell with an inflatable fence is carried out directly in the oil spill zone, the cavities of the shell and the inflatable fence are filled with hot air.

However, such technologies have low productivity, high labor intensity, limited possibilities of appon, while oil is collected from a small area of the water area.

A method for removing oil from under the ice through an ice-hole made in the ice. The device for implementing the method includes arrows passing under the ice in two different directions from the hole so as to form an angle of less than 180 degrees to each other. The method involves the use of a device for collecting oil, placed in the ice hole and an oil water flow device placed at the level of the lower surface of the ice to ensure flow direction to the hole between the arrows [10].

Methods for removing oil pollutants from the surface of water using oil arrows and skimmers equipped with rotating brushes have become widespread. Oil is also collected using a long rope made of hairy yarn that can absorb oil. It moves along the surface of the water collecting oil, then it is taken out of the water and squeezed out, after which the cycle is repeated. These methods, which have proven themselves quite effectively in open water, turned out to be ineffective for extracting oil from an environment containing ice or from under the ice cover [11, 12].

The Oil Spill Cleaner [13] is a multihull vessel containing the middle and side hulls. The vessel is equipped with a separator detaching the ice blocks by moving them between the middle hull and the side hulls from bow to stern (Fig. 1).

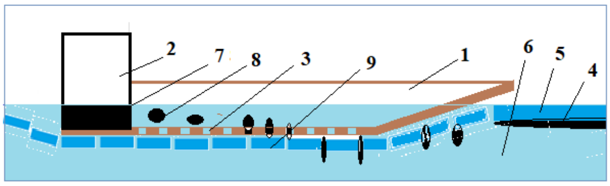

Fig.1. A vessel for removing oil contaminants in ice cover conditions (1 - icebreaker vessel, 2 - oil collection tank, 3 - separator, 4 - oil spill under the ice, 5 - ice cover, 6 - water, 7 - collected oil, 8 - fragments of oil in water, 9 - cracked ice) [13]

The separator (Fig. 1) is a grid that separates ice from oil. The vessel pushes the ice down through the separator, and while the water and oil pass through the separator, oil is separated from the water and collected in a container. The oil can be separated from the water using a collection device, which can be, for example, a brush skimmer.

3 Technology and equipment for oil removal from under the ice

The purpose of the technology for removing oil pollution from under the ice cover, proposed in this article, was designed to ensure the above requirements and conditions for effective elimination of the consequences of an accidental oil spill.

The proposed technology [14,15] consists in localization of an oil or oil product slick and subsequent removal of oil or oil product by pumping it into an oil receiver. At the same time, a well is drilled in the area of localization of the oil or oil product slick in the ice cover; a swirler with an evacuation device is submerged into the slick area, the swirler rotation creates a vortex funnel in the water under the ice (Fig. 2), in which oil is collected and it is pumped out from the vortex funnel formed (Fig. 3).

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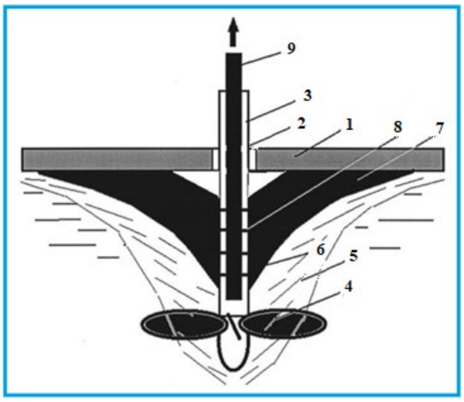

Fig. 2. Scheme of the formation of a vortex funnel under the ice cover (1 - ice cover, 2 - well, 3 - hollow swirler shaft, 4 - swirler, 5 - vortex funnel, 6 - oil in a vortex funnel, 7 - oil spill under the ice 8 - perforations in the hollow shaft, 9 - pumping pipe oil)

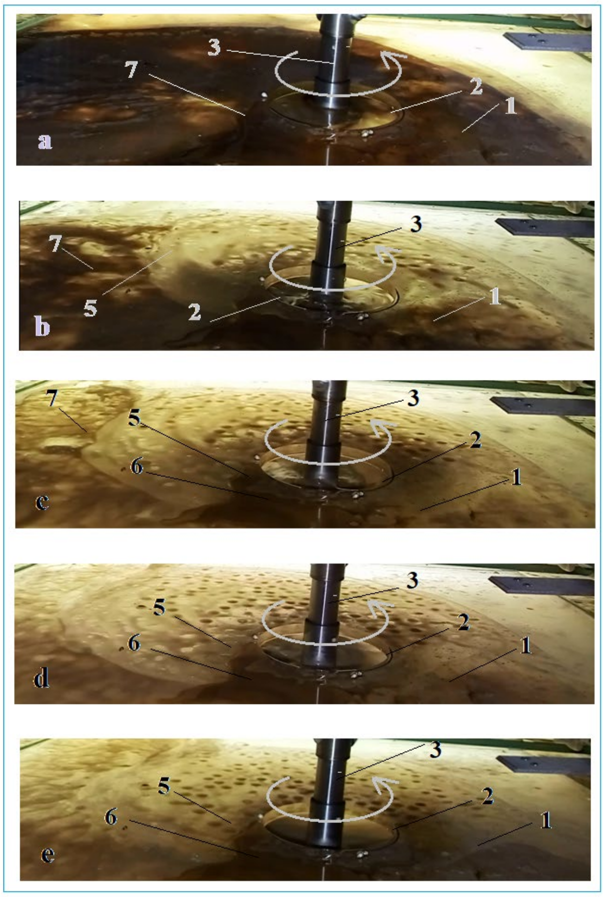

Fig. 3. Stages of vortex formation under the ice cover (a - initial state; b, c, d - the process of oil pulling into the vortex funnel; e - the end of the oil removal process. 1 - ice cover, 2 - well, 3 - hollow swirler shaft, 5 - vortex funnel, 6 - oil in vortex funnel, 7 - oil spill under the ice)

To remove oil pollution, the oil slick is first localized, which can be done, for example, by placing the boom 10 under the ice cover 1 (Fig. 4a) by transporting it by underwater drones or submersibles [2].

Above the area of the localized oil slick 7, a mobile installation for drilling and pumping oil 11 is placed (Fig.4a) and a well 2 is drilled in the ice cover 1, a swirler 4 with a pumping device is immersed through it into the slick area (Fig.4b).

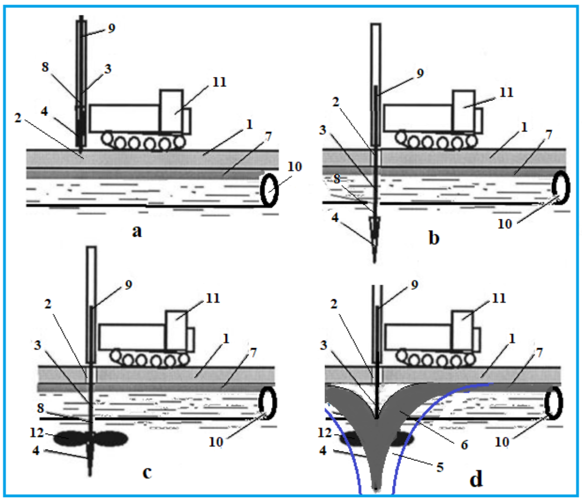

Fig. 4. Scheme of deployment and operation of equipment to remove oil spills from under the ice (a - preparation for drilling a well, b - drilling a well, c - deploying a swirler, d - pumping oil from under the ice cover. 1- ice cover, 2 - well, 3 - hollow swirler shaft, 4 - swirler, 5 - vortex funnel, 6 - oil in the vortex funnel, 7 - oil spill under the ice, 8 - perforations in the hollow shaft, 9 - oil pumping pipe, 10 - booms, 11 - mobile rig for drilling and pumping oil, 12 - blades)

After immersion of the swirler 4 into the water to the required depth, the blades 12 of the swirler 4 (Fig. 4c) open and the rotation of the swirler 4 creates a vortex funnel 5 in the water under the ice (Fig. 4c), which collects oil 7 into it, by capturing it into a vortex funnel 5.6. Then, oil 6 is pumped out of the vortex funnel 5 (Fig. 4c). When a vortex funnel 5 forms in the water (Fig. 2 and Fig. 4), due to the difference in the densities of water and oil, lighter oil 6 is collected in the central part of the vortex funnel 5. Further, through perforations 8 in the hollow shaft of the swirler 4, oil 6 through a pipe for pumping oil 9 is pumped out into a tank for collecting oil products (Fig. 5).

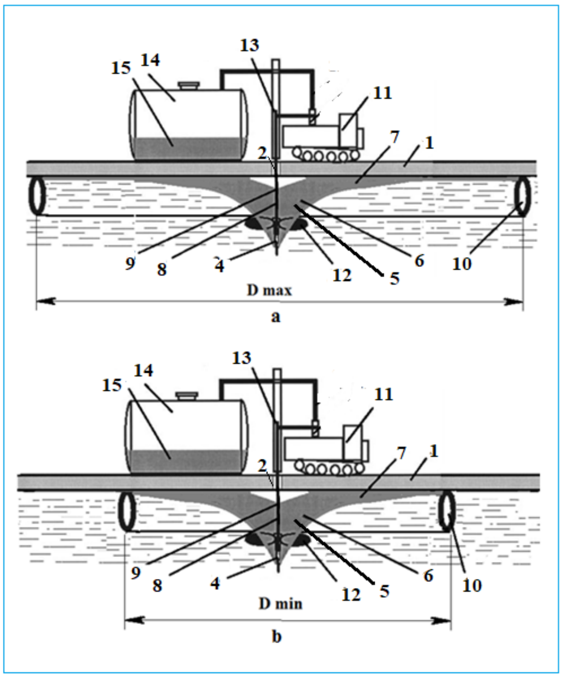

Fig. 5. Schematic diagram of a mobile installation for removing oil spills from under the ice. (a - the beginning of oil spill response, b - oil removal with a gradual decrease in the area covered by booms. 1 - ice cover, 2 - well, 3 - hollow swirler shaft, 4 - swirler, 5 - vortex funnel, 6 - oil in a vortex funnel, 7 - oil spill under the ice, 8 - perforations in the hollow shaft, 9 - pipe for pumping oil, 10 - booms, 11 - mobile rig for drilling and pumping oil, 12 - swirler blades, 13 - pipeline for pumping oil into tank, 14 - tank for oil, 15 - pumped out oil)

Further, through the perforations 8 in the hollow shaft of the swirler 4, the oil is pumped through the oil transfer pipeline 13 to the oil collection tank 14 (Fig. 5). Then, after removing the oil, the blades 12 of the swirler 4 are folded and the swirler 4 is removed from under the ice. The mobile unit is folded down and, if necessary, moved to another site.

At formation of two-phase ("water-oil") vortex funnel (Fig. 6 and Fig. 7), the following factors act. When the swirler blades rotate from the underlying water layers to the upper water layers and from them to the oil layer, the rotation of each layer (conventionally adopted in this model) is transmitted by the friction force between the layers in question (Fig. 6). Since energy losses occur in this case, the angular velocity of each successive layer decreases when approaching the ice cover. At the same time, the friction force between the water layers is much greater than at the “water-oil” interface, which leads to a sharp lag in the angular velocity of the oil layer rotation from the water layers.

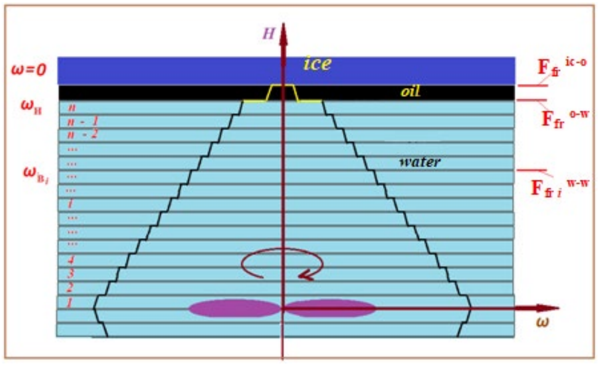

Fig. 6. Distribution of angular velocities at the initial stage of vortex vortex formation. (F_{fr}^{ic-o} is the friction force between ice and oil, F_{fr}^{o-w} is the friction force between oil and water, $F_{fr\,i}^{w-w}$ is the friction force between layers and water, ω is the angular velocity of rotation of the swirler, ω_n is the angular velocity of rotation of the layer oil, $\omega_w^{\,i}$ - angular velocity of rotation of the *i*-th layer of water)

As a result of this, the formation of a vortex water funnel occurs in advance. In addition, a larger specific gravity of water (Pw) creates an advantage in the centrifugal force of each layer of water (Fcf w), which affects the resulting strength of the i-th layer of water (Rin), which significantly exceeds the resulting force of the i-level of oil (Rn) and, being the dominating force, collects the vortex funnel of oil into the inner cavity of the vortex funnel. Moreover, the lower specific gravity of oil also contributes to its accumulation above the water funnel.

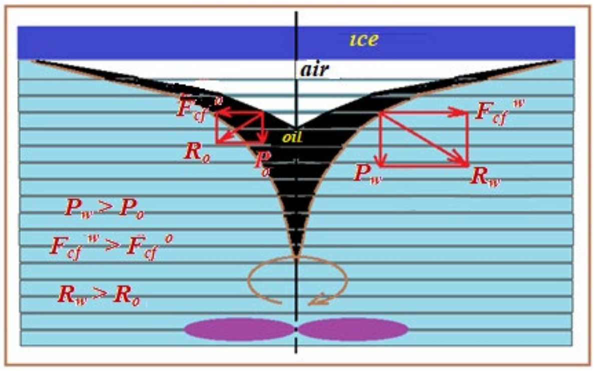

Figure 7. Factors influencing the formation of a vortex funnel. ($F_{cf}^{\,o}$ - centrifugal force acting at the *i* - level of the oil funnel, $F_{cf}^{\,w}$ - centrifugal force acting at the *i* - level of the water funnel, P_o - gravity acting at the *i* - level of the oil funnel, P_w - gravity at the i - level funnel, R_w is the resultant force acting at the *i* - level of the water funnel, R_o is the resultant force acting at the *i* - level of the oil funnel)

The forces acting in the binary vortex funnel of the "water-oil" system can be represented as the following expressions:

$$Pw > Po, \qquad (1)$$

where: Pw - the force of gravity acting at i - the level of the water funnel;

Po - the force of gravity acting at the i - level of the oil funnel.

$$Fcf\ w > Fcf\ o, \quad (2)$$

where: Fcf w - centrifugal force acting at i - water funnel level;

Fcf o - centrifugal force acting at the i - level of the oil funnel.

$$Rw > Ro, \quad (3)$$

where: Rw - the resulting force acting at i - the level of the water funnel;

Ro - the resulting force acting at the i - level of the oil crater.

Further, since the molecular interaction forces of the "oil-oil" system are greater than those of the "ice-oil" system, when oil is pumped into the interior of the vortex funnel (as a result of the effect of the vortex funnel effect), oil formed in the vortex funnel removes oil layers from the “ice-oil” boundary, cleaning its surface, which is replaced by the “ice-water” boundary. The latter effect is also confirmed by experiments (example.g., the series of photographs in Fig. 3), where gradual removal of oil from the “ice-oil” boundary is observed.

4 Conclusion

Despite some success in the development of new technologies for oil spill response in the Arctic, they are usually not completed due to insufficient funding and lack of interest from oil companies.

A new method of oil pollution removal has been proposed and investigated, which consists in localizing an oil slick and then removing it from under the ice using the vortex funnel effect and pumping it into an oil receiver.

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