Eurasian Chemico-Technological Journal 15 (2013) 275-281

Burning Oil Layer on the Surface of Water

Z.A. Mansurov*, B.T. Lesbaev, N.G. Prikhodko, Yu.V. Kazakov, Zh. Ualiyev

The Institute of Combustion Problems, 172, Bogenbai Batyr St., 050012, Almaty, Kazakhstan

Abstract

The results of investigations on combustion of Karazhanbas and Tengiz oil on the surface of water are presented. The minimum thickness of oil layer allowing to initiate and support the process of combustion is stated to be lie in the range of 3–5 mm. For ignition and maintenance of stable combustion of oil on water surface, a synthetic sorbent is proposed. It is found that, the synthetic sorbent accelerates the combustion process of oil on water surface threefold in comparison with the combustion process of oil without a sorbent. It is shown that the remaining mass of oil on water surface after combustion process termination, presents a bituminous substance having a good coalescence and high adhesion that allows to collect it with high efficiency by a mechanical method. The process of ignition and combustion of oil on the water surface is significantly affected by contained in it combustible volatiles. In this paper, on the example of oil from Tengiz field, the regularities of the influence of temperature and salinity on evaporation of light fractions and the burnout process are revealed. It is determined that the degree of water salinity does not affect the process of evaporation of light fractions of oil, this process is significantly affected by temperature water. The research has shown that the important factors that influence the degree of burning of the oil layer on the surface of water is the degree of salinity and the initial temperature of water, while these relationships are complex. Revealed that the salt water burning process more profitable to produce oil at water temperatures above 20 °C. The developed model in has been supplemented with a coefficient of thermal conductivity as a function depending on temperature. Numerical results more accurately predict the experimental observations. The reason is that thermal diffusivity is determined more precisely.

Introduction

A significant increase in consumption of petroleum products by mankind from the middle of XX century, led to globalization of environmental problems associated with environmental pollution is modern society. Especially important is the problem of pollution of water areas with oil. Emergency oil spills during transportation of oil by water can considerably damage the ecosystem and lead to negative social consequences.

Annually, the seas and oceans intake 5–10 million tons of crude oil and refined products from various sources of the total mass of oil falling annually into the seas and oceans, about 35% is lost in the course of transportation of oil, about 32% come with the flowing rivers and 10% come from urban and industrial waste management of coastal areas, from the atmosphere and natural sources [1]. The amount of oil equal to 80–90 mg is sufficient to cover 1 m^2 of surface water. Apart from the category of oil spill, the first measures should be directed to its rapid localization to avoid the distribution of further contamination of new sites [2]. Oil falling onto the water surface, prevents penetration of sufficient sunlight and reduces the level of oxygen dissolved in water and it does much harm to the flora and fauna of water area.

Therefore, development of effective methods for liquidation of oil spill elimination is a task of great importance [3]. Now, one of the most common methods for liquidation of oil spills on the surface is burning. For a stable self propagation of the flame, at least 2% of the total heat energy of combustion must return to the layer of oil [3, 4]. For this, a special role is played by the thickness of oil layer, which in its turn, is highly dependent on the individual properties of the spilled oil and the effect of temperature and salinity.

Burning oil requires minimal training and experience of the staff due to the use of simple and accessible rules of moving booms, as well as ease of

---

* Corresponding author. E-mail: zmansurov@kaznu.kz

© 2013 Al-Farabi Kazakh National University

ignition of oil, in which all personnel are at area safe distance from the combustion zone. Burning can be used where other methods are not effective spill response (or feasible), and can be done in parallel with other methods after determining an appropriate method for a particular site or geographic region.

In this work we studied the effects of temperature and salinity on evaporation of the light end sand the combustion of oil from Tengiz.

Experimental

Investigations on combustion of Karazhanbas oil on water surface were carried out. The experimental apparatus includes a vessel (1) with the volume of 50 liters with a built in watch window in the middle of the vessel. For localization of oil sample on the surface of water and production of a layer with the required thickness we used a restricting frame (2) with the size of 15×15 cm and the height of 6 cm made of iron strip. For prevention of soot emission to the atmosphere the apparatus is equipped with exhaust hood (3) joined by pipe-line (4) through soot collector (5) with air exhauster (6).

The temperature profile of the flame, oil layer and the layer of adjacent water were measured using of a system measurement of zone temperatures, which provides continuous temperature monitoring in the experimental process.

The oil ignition is produced by a system of remote initiation of combustion process. The system of remote ignition includes a transmitter-receiver activated by a radio-signal followed by powering of glower, which is located in igniting composition providing a strong exothermal influence sufficient for oil ignition. Experiments with oil combustion on water surface were conducted with the help of the apparatus pictured in Fig. 1.

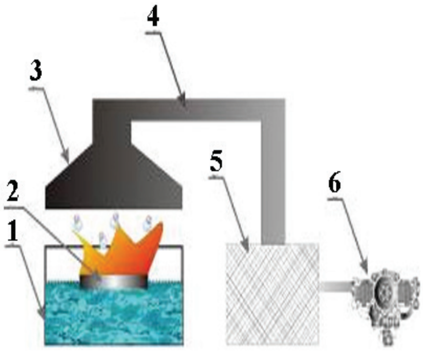

Fig. 1. The scheme of experimental apparatus for combustion of oil on the surface of water: 1 – water vessel; 2 – the restricting box for oil; 3 – exhaust hood; 4 – pipeline; 5 – soot collector; 6 – air exhauster.

To determine the amount of evaporated oil over time, prepare system "water − oil". To do this, pour 300 ml of synthetic salt water into a plastic cup with the volume of 500 ml. Add 50 ml of oil to the same container. The diameter at the level of coverage of the oil layer was 8.2 cm (coverage = 52.78 cm^2). The thickness of the oil layer was ~ 9.5 mm. Salinity ranged from 0 to 18‰, temperature 0 ° to 25 °C. We registered the initial mass and then measured the residual mass after 1, 2, 3, 4 and 5 hours.

Discussion of Results

The experiments were carried out with oil from Karazhanbas field. This oil is heavy, highly resinous, sulphurous, with a low content of in paraffin, and is characterized by a low yield of floating fractions (the yield of light fractions boiling away up to 350 °C, makes up 27%) [5, 6].

A key moment for self-propagation of the flame of liquid fuels is the thermal balance on its surface. It is stated that it is practically impossible to organize the process of self-propagation of oil flame or oil products on the surface of water 15 minutes later after the beginning of spill [5].

The reason is that oil being in contact with the surface of water forms water-oil emulsion and oil must be intensively heated to get ignited. Experimental studies have shown [3] that heating of the surface of water-oil emulsion leads to its separation into oil and water and the combustion process is supported by surface evaporation from the surface of separated oil. This process is very important at the very beginning of the ignition process of water-oil emulsion and the burning composition must have the property that would compensate the volume cooling and bring the water-oil emulsion to its separation. Thompson and et al. [3] have proposed a simple balance of energy distribution at combustion of oil layer on the surface of water:

$$\textit{Useful power} = 0.02Q_{comb} - Q_{Lo} - c_{po}(T_{ov} - T_a),$$

where Q_{comb} is the energy produced in the process of oil combustion, Q_{Lo} is the energy consumed for oil evaporation, c_{po} is specific heat of oil, T_{ov} is evaporation temperature of oil, T_{a} is temperature of the environment.

It is assumed that 2% of the total heat energy of oil combustion is returned to fuel for maintenance of evaporation and self-propagation of the flame. The calculation made according to the formula has shown that the useful energy necessary for maintenance of combustion process of water-oil emulsion is equal to 3.45105 J/kg. In this work, for ignition of oil the following composition of the kindling mixture was used, magnesium (90-94%), aluminum (0.5-8%), zinc and manganese (1.5-8%) with the density of 1.80-1.83 g/cm^3, T_{melting} = 630-635°C and maximum combustion temperature T_{burning} = 2000 °C. The combustion process of water-oil emulsion can be divided into four stages. The first stage – the influence of the external heat flow on the emulsion upper layer that leads to its heating and separation to oil and water. The second stage – continuous heat supply resulting in evaporation of the separated oil. The third stage – evaporated oil is ignited and the energy released during combustion increases the thickness of separated oil layer that enhances the evaporation degree and self-propagation of the flame. In the fourth stage, in the course of burning, the layer of water-oil emulsion gets exhausted, an intensive outflow of heat occurs due to the adjoin water surface and the flame goes out.

The experiments were carried out with oil in the amount of 250 ml poured into the restricting box with the size of A×B×H = 15×15×6 cm (A – width, B – length, H – height of the box). At this volume of oil its height above the water surface was 1 cm. The oil layer was uniformly coated with synthetic sorbent with the thickness of 0.5 cm. Burning time of oil with the volume of 250 ml was 5 minutes and 30 seconds. The residue of 50 ml was a bituminous mass with good adhesion. It was stated experimentally that the combustion process of oil with a sorbent reduces the combustion time tree-fold, compared with the combustion process of oil without sorbent (Fig. 2a).


a b

Fig. 2. The general appearance of a synthetic sorbent (a) and photo of the combustion process of oil with a synthetic sorbent (b).

Reduction of the combustion time can be accounted for the increase of combustion efficiency due to involvement of light fractions adsorbed on the surface of a synthetic sorbent (Fig. 2b). The results of oil sorption by a synthetic sorbent are shown in Table 1.

Table 2 shows the temperature characteristics during oil combustion on the water surface using a synthetic sorbent. One of the most distinctive features of burning oil on the water surface is a very rapid combustion during the last 30 minutes. This period of intensive combustion occurs, when the oil layer becomes thin and a sufficient amount of energy from the flame causes boiling of the adjoining water layer and its evaporation.

Table 1

The results on oil sorption by a synthetic sorbent (I – the form of a sorbent, II – the mass of pure sorbent, g, III – time of sorption, min., IV – the mass of a sorbent with oil, g, V – the increase in weight, %)

I	II	III	IV	V
Holistic peace	3.7	10	25.4	686
In the form of chip	1.7	10	33.8	1988

Table 2

Temperature profile of the flame according to the height with the use of a synthetic sorbent (I – thermocouples, II – temperature °C during the time passed since the beginning of combustion, min)

I	II			
	1	3	6	7
TP1 (in the layer of oil-water emulsion)	130	180	230	50
TP2 (in the layer of oil at the depth of 0.5 cm)	180	320	465	440
TP3 (in the flame at the height of 10 cm)	730	920	850	680
TP4 (in the flame at the height of 15 cm)	790	1070	1020	820

The explosive surface raises the oil drops to the flame, and the accelerating combusting process is accompanied by a strong sound effect. The boiling of oil continues after the flame dying down. Figure 3 shows the process of intensive combustion with emission of vapor to the flame (Fig. 3a) and swelling the process of oil mass swelling after completion of burning (Fig. 3b), due to continued boiling of water sublayer. The soot, formed under these conditions, contains a tarry component.


a b

Fig. 3. The photo of an intensive combustion process with emission of vapor to the flame (a) and swelling process of oil mass after completion of burning due to continued boiling of water sub layer (b).

As a result of the experimental studies it is stated that minimum thickness of oil layer allowing to initiate and maintain the combustion process is in the range of 3-5 mm.

The residual products of oil combustion is bituminous mass with a good coalescence and strong adhesion that allows to collect it by a mechanical way from the surface of water.

The process of oil combustion on the water surface is accompanied by formation of soot. To determine the morphology and sizes of the formed soot particles, the electron-microscopic studies were carried out. The analysis of electron-microscopic images of soot particles which were obtained under different conditions have shown that the shape of soot particles is close to a spherical one with the diameter of 30-50 nm. There takes place coagulation of soot particles generated by simultaneously formed polycyclic aromatic hydrocarbons, which adsorbed on the surface of soot particles.

The process of ignition and combustion of oil on the water surface is significantly affected by the content of flammable volatile fractions in it. Intensive evaporation of light ends, spilled of oil on the water occurs in the first 5-8 hours, while the evaporation process is significantly affected by water temperature. Investigations were carried out to determine the effect of temperature, salinity of water and time on the process of evaporation of light fractions of oil from Tengiz field. The results of the studies on the evaporation process depending on the temperature and salinity of water is shown graphically in Fig. 4.

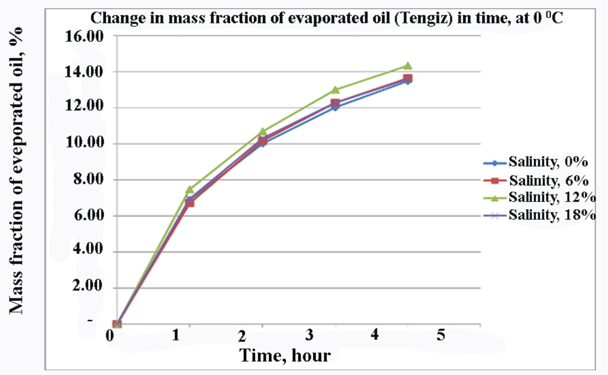

Fig. 4. Measurement of the change of mass fraction of vaporized oil (Tengiz) time T_{water} = 0 °C.

Analysis of the experimental data shows that the process of evaporation of saline water has no effect. The difference in the fraction of total mass of light fractions depending on the degree of water salinity (0-18‰) is within a metrological errors. Mass fraction of evaporated oil increases with the increase in temperature. The results of the research have show that oil on the surface of water evaporates rapidly in the first 4-6 hours, after which the process proceeds in slow stages. The data obtained on evaporation of light fractions of oil allow determining the period of time during which it is possible to liquidate oil spills by the method of burning. Besides, the investigations allow to evaluate the degree of air pollution on account of evaporation on products on the territory of oil spill. An important factor influencing the steady flame propagation during combustion of oil on the water surface is the degree of salinity. The basic compounds making the water the ocean and seas saline are potassium and sodium chlorides. It is known that sodium chloride is an inhibitor (flash suppressor) of the burning process. Another factor that has a significant impact on the process of burning of oil layer on the water surface is the initial temperature of water, as with burning of oil layer and the decrease in the thickness of the film will be important role will be played by the heat sink, which directly depends on water temperature.

Table 3 and Fig. 5 present the experimental results of research on combustion of oil from the Tengiz field on the surface of water with respect to temperature and salinity.

Table 3

The oil from the Tengiz field, $\Delta\tau_{evaporation}$ = 4:00, V_{oil} (original) = 1000 ml, the thickness of the layer of oil prior to combustion = 5.00 mm, flame temperature = 900–1150 °C (I – T_{water} and salinity of water, II – V_{oil}, after combustion, ml, III – the thickness of the oil layer after combustion, mm, IV – the temperature of water on the depth, cm, V – burning time, s)

I	II	III	IV					V
			1	2	3	4	5	
7 °C, 0‰	260	1.30	36	15	12	7	7	216
13 °C, 0‰	250	1.25	37	20	18	13	13	215
20 °C, 0‰	240	1.20	52	27	24	20	20	255
25 °C, 0‰	230	1.15	55	32	30	25	25	200
7 °C, 6‰	280	1.40	33	14	12	7	7	205
13 °C, 6‰	260	1.30	37	20	17	13	13	207
20 °C, 6‰	250	1.25	40	25	24	20	20	220
25 °C, 6‰	240	1.20	42	28	28	25	25	217
7 °C, 12‰	300	1.50	35	14	12	7	7	216
13 °C, 12‰	270	1.35	40	19	17	13	13	218
20 °C, 12‰	270	1.35	43	30	22	20	20	220
25 °C, 12‰	250	1.25	45	32	28	25	25	223
7 °C, 18‰	320	1.60	26	20	10	7	7	191
13 °C, 18‰	280	1.40	33	17	15	13	13	192
20 °C, 18‰	260	1.30	39	25	23	20	20	190
25 °C, 18‰	240	1.20	45	30	28	25	25	192

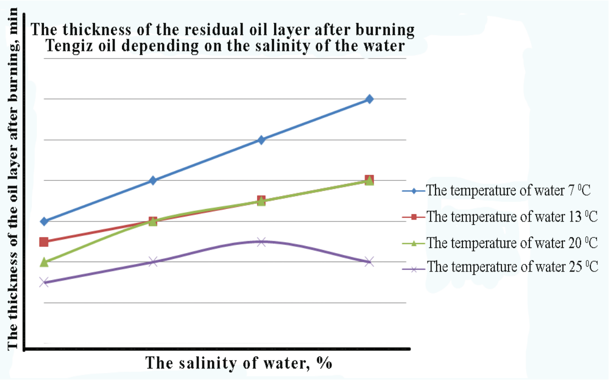

Fig. 5. Dependence of the thickness of the residual oil layer after burning on temperature and salinity of water (Tengiz).

Depending on weather conditions, oil, when being in contact with water undergo us significant physical changes there mainly takes place intensive emulsification of oil with water. Formation of water-oil emulsion exerts a significant effect on the efficiency of burning an oil spill. Experiments were conducted to determine the water-oil emulsion to blend Zhanazhol-Buzachi 70/30 at 12‰ salinity and temperature of 6 °C (Table 4).

Table 4

Water saturation blend Zhanazhol-Buzachi 70/30 at salinity 12‰, 6 °C and wave height of 10 cm (I – mixing time, hour, II – weight of the original oil, g, III – weight of oil + emulsified water, g, IV – weight of emulsified water, g, V – water saturation, %)

I	II	III	IV	V
1	7.33	8.54	1.21	16.5
4	8.45	10.37	1.92	22.7

Experimental studies on burning Tengiz oil on the surface of water have showed that with the increase in concentration of salt in water at temperatures below 10 °C the burning time decreases (with other things being equal), and as a result, the less amount of the spilled oil burns out. The time of burning decreases with the increase in concentration of salt in water due to the increased activity of sodium chloride as a flame retardant. This dependence is observed at low water temperature (7 °C), but at higher temperatures (25 °C) the effect of salinity on the amount of oil residue after burning is less pronounced. The volume of oil burned at the temperature of 25 °C and 18‰ salinity is comparable to the volume of oil burned at the temperature of 25 °C and salinity 0‰. From these data, we can conclude that, on the process of steady flame propagation. The higher salinity of water is more profitable for the burning oil of Tengiz profitable to produce at water temperatures above 20 °C. In water with low salinity temperature of water has less effect on the combustion process and the effectiveness of the method of burning Tengiz oil in water with low salinity does not decrease with decreasing temperature.

When carried out investigations on burning Tengiz oil on the surface of water, changes in water temperature were registered with in height (1, 2, 3, 4, 13 cm from the border of oil-water). After termination of combustion total water temperature was measured. These studies have shown that combustion of oil increases in water temperature in height (from the border of oil-water) is not even. The upper layer of water adjacent to oil begins to boil. Changes in water temperature with depth, when burning the Tengiz oil, are as follows in average: at a depth of 1 cm – an increase by 20-30 ºC, at a depth of 2 cm = 3-10 ºC, at a depth of 3 cm = 2-5 ºC from the initial temperature. Warming of the water column is terminated at the depth of 4 cm. The overall temperature of water (48 liters volume) increased in average by 2-6 ºC. Given the mass of water, its heat capacity and changes in water temperature during combustion of oil on the surface, we calculated the approximate value of the energy released by combustion of oil, it is about 4000 kJ.

Thus, when burning oil about 2 kJ of heat per of 1 cm^2 is transferred to the volume of water. At some stage, oil burning stops, due to the small thickness of the oil layer and a large cooling effect of water, the amount of the released energy being not sufficient to vaporize oil.

Mathematical Model and its Results

In paper [3], the combustion process of water-in-oil emulsion layers floating on the top of the water body is modeled using a comprehensive mathematical treatment, and the results are compared with the data obtained in them lab. For modeling purposes, it is divided into three regimes as follows:

1. Initial Regime ($0<t<t_1$): A constant radiation heat flux source is incident on the surface to heat the emulsion and eventually reaches the upper surface temperature of the emulsion to break.
2. Intermediate Regime ($t_1<t<t_2$): Continued input of heat grows the oil layer and thins the emulsion layer. The temperature of the oil layer increases whereas the oil-emulsion interface temperature remains constant at the emulsion breaking temperature.
3. Final Regime ($t>t_2$): The surface temperature of the oil now is equal to at the oil vaporization temperature. The combustion process continues until the emulsion layer completely breaks up and depletes, oil layer continues to burn and, finally, extinction occurs because the loss of heat becomes so

large there is no sufficient energy to cause pyrolysis of oil.

Model (I) in [3] changed model (II) with thermal diffusivity, which is defined as a function of temperature. Figure 6 shows the measured ratio of thermal diffusivity of emulsions with different water content on the thermal diffusivity of oil. In model (II) input parameters, initial and boundary conditions are same as in [3].

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\alpha(T)\frac{\partial T}{\partial z}\right) + f,$$

Governing equation (a one-dimensional process is assumed):

$$\alpha(T) = \begin{cases} \alpha_0(T), & if\ z \in [H, S] \\ \alpha_{\text{в}}(T), & if\ z \in [O, H] \\ a_w(T), & if\ z \in [-\infty, 0] \end{cases}$$

where T is temperature (K), t is time (s), z is height on surface of water (m), $\alpha(T)$ is thermal diffusivity (m^2/s):

$$f = \begin{cases} \dfrac{C_0 \dot{q}'' \beta e^{-\beta(S-z)}}{\rho_0 C_{po}}, & if\ z \in [H, S] \\ 0 \quad , & if\ z \notin [H, S] \end{cases}$$

H is the border between emulsion and oil, S is the border between oil and oil vapors (Fig. 6), $\alpha_o(T)$ is thermal diffusivity of oil, $\alpha_e(T)$ is thermal diffusivity of emulsion, $\alpha_w(T)$ is thermal diffusivity of water, f is heat flux rate (K/s);
C_0 is fraction of incident heat flux not absorbed at the surface, q is incident heat flux (W/m^2), β is inverse optical depth (m^{-1}), ρ_o is density of oil (kg/m^3), c_{po} is specific heat of oil (J/kg K).

Three different values of time for separation are reported in Table 5. Findings were calculated at critical heat flux value (which depends on the water content of the emulsion). In Fig. 7, it can be seen that the model predictions show a trend similar to those of the experimental observations. However, the trends of the model predictions match the trend of the experimental observations better in Model (II) than in Model (I).The reason is that the thermal diffusivity is defined more precisely.

Table 5
Comparison of model predictions of emulsion separation time with the experimental data

Water, %	Time for emulsion separation at critical heat flux (s)		
	Experimental [3]	Model (I) [3]	Model (II)
20		540	765
30	600	350	580
40	430	375	460
50	440	470	400

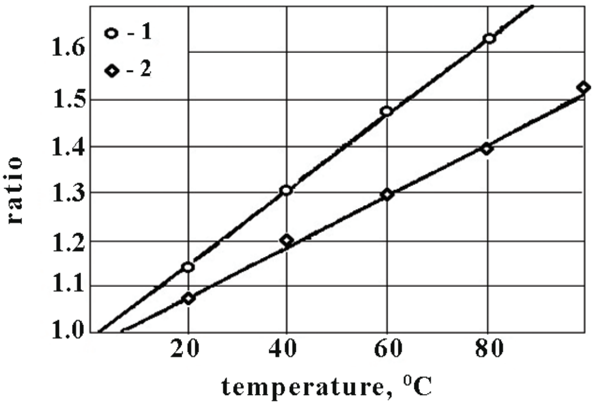

Fig. 6. The ratio of thermal coefficients depending on temperature: 1-30% (vol.) water content of the emulsion and 2-40% (vol.) water content of the emulsion.

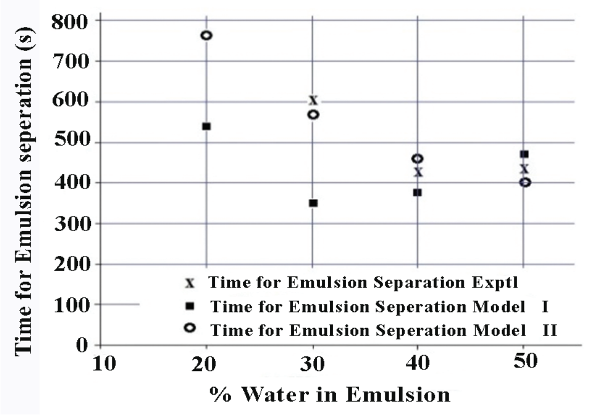

Fig. 7. Comparison of models for prediction of time for emulsion separation with the experimentally observed values.

Conclusions

On the example of Karazhanbas oil it is stated that minimum thickness of oil layer allowing to initiate and maintain the combustion process is in the range of 3-5 mm. The proposed synthetic sorbent accelerates the combustion process of oil on the water surface tree-fold compared with the combustion process of oil without a sorbent that is explained by significant sorption of light fractions and their involvement in the combustion process. It is shown that the remaining mass of oil on the water surface after termination of the combustion process ending, is a bituminous mass which has a good coalescence and strong adhesion, that allows to collect it by a mechanical way from on the surface of water.

It is found that the evaporation of oil (Tengiz) from the surface of water is not dependent on salinity of water. Mass fraction of evaporated oil increases with the increase in temperature, and the largest loss in weight by evaporation occurs in the first 3 hours. The increase in concentration of salt in water increases the volume of unburned residue of oil (Tengiz) due to the influence of sodium chloride which is fire inhibitor.

References

1. Options for Minimizing Environmental Impacts of Freshwater Spill Response. American Petroleum Institute. Prepared by E.N. Owens (OCC Ltd.) and J. Michel (RPI) for American Petroleun Institute, Washington DC, and National Oceanic and Atmospheric Administration, Seattle WA, American Petroleum Institute Pub. No 4558 (1994), 146 p.
2. A.A. Shavykin, G.V. Ilyin, Ocenka integral'noj ujazvimosti Barenceva morja ot neftjanogo zagrjaznenija [Integrated vulnerability assessment of the Barents Sea from oil pollution], Murmansk: Murmansk Marine Biological Institute, (2010) 110 p.
3. A.Y. Walavalkar, A.K. Kulkarni, Combust. Flame 125 (2) (2000) 1001-1011.
4. C.H. Thompson, G.W. Dawson, G.L. Goodier, Combustion: An Oil Spill Mitigation Tool, US Department of Energy, Washington, DC, 1979, P. 53.
5. N. Nadirov, Vysokovjazkie nefti i prirodnye bitumy: Harakteristika mestorozhdenij. Principy ocenki resursov [Heavy oil and natural bitumen, Characteristics of deposits, Principles of evaluation resources], Gylym, Almaty, (2001) 337 p.
6. Z.A. Mansurov, B.T. Lesbaev, N.G. Prikhodko, B.K. Tuleytaev, D.D. Priimak, Yu.V. Kazakov, Zh.A. Kulekeev, G.K. Nurtaeva, A.N. Dzhunusov, N.K. Smailov, B.Z. Mansurov, B.G. Topanov, Nonequilibrium Processes, Plasma, Combustion, and Atmospheric Phenomena (2012), P. 330-336.

Received 15 July 2013