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Oil Pollution Prevention of Natural Waters by Incident Early Detection on Oil Pipelines in Water Body Crossing Places

Mikhail V. Begun[a], Anna M. Ledovskaya[b,*], Ekaterina A. Kupressova[b], Sergey V. Romanenko[b]

[a]Russian Emergencies Ministry Main Office for Tomsk Region, Mira Avenue, 26, Tomsk, Russian Federation, 634057
[b]National Research Tomsk Polytechnic University, Lenin Avenue, 30, Tomsk, Russian Federation, 634050
sokolovaam@tpu.ru

Oil and oil products remain a widespread pollutant of water bodies on the territory of Russia. It is connected with the great length and complexity of the hydrocarbon transport pipeline network. The majority of pipelines are operated in conditions of bad climate and geography. The places of underwater oil pipeline crossings have the greatest risk of an accident with the probability of contaminating water bodies. Applied pipeline monitoring systems do not provide detection of early oil leak stages (less than 1 % of pipeline capacity). Pipeline section can be for a long time in this situation until emergency occurs, it can result in significant environmental damage. It is proposed to use screening method for early leak detection, based on aromatic fraction fluorescence response of oil and oil products in water. Fluorescent sensor operates in the excitation spectral region of 340 – 360 nm to reduce a signal dependence on the composition of oil and oil products. For indirect confirmation of oil contamination, it is suggested to use additional indicator – specific conduction (mainly connected with chloride ion concentration). The proposed screening control scheme for oil pollution prevention takes into account the composition of oil pipeline content and the content of organic and biological substances in the water body. This approach eliminates the influence of natural substances on the fluorescent response because this factor is taken into account in the background response. Early leak detection thanks to the screening system reduces rupture probability by at least one order. In addition, it will prevent oil pollution of water bodies and reduce environmental damage.

1. Introduction

Water potential on the territory of Russia is one of the highest in the world. The river net of Russia is one of the most developed in the world. There are about 2.7 M of rivers and streams on the state territory (Ministry of Natural Resources and Environment of the Russian Federation, 2016). However, the state of surface waters as a result of the sharply increased anthropogenic load is deteriorating at present, especially for small rivers. Oil products are the most common pollutants in surface waters (Vorobiev and Noskov, 2015). It is especially worth noting that among all the causes of pollution oil and oil products are getting into hydrosphere objects in case of accidents in oil pipelines passing through water barriers (Altunina et al., 2014).

Tens of thousands of cases with pipeline failures such as a hole or a rupture are observed annually, which leads to significant losses of hydrocarbon crude and to the negative impact on the environment. This is due to the fact that oil pipelines are operated in difficult conditions (Anishchenko et al., 2017). The places of underwater oil pipeline crossings have the greatest risk of rupture as the profile of the underwater pipeline crossing on the shore sections and within the channel part has curvatures in the vertical plane (Burkov et. al., 2014). Pipelines have additional stress due to the river channel and floodplain processes. An oil spill in water bodies has larger extent than an oil spill on land. When oil products get into hydrosphere objects, their spreading occurs relatively fast (Environmental pollution centers, 2017). As a result of oil pollution, there is a decrease of water aeration and toxic effects on flora and fauna leading to a feedstock reduction, diseases, and death of eggs, larvae, tiny and adult fish (Svarovskaya and Yashchenko, 2016).

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Currently used leak detection systems for the oil pipelines do not allow their early detection with minor damage at the initial stage of the accident (Vairo et al., 2017). A damaged pipeline section can be a long period of time in this state up to the occurrence of a large-scale rupture. Harm to water body can become significant during this time.

2. Oil pipeline incidents

Russian pipeline system has an extensive network and a great length which has no analogues in the world. Nowadays it provides transportation of more than 750 Gm^3 of gas and more than 500 Mt/y of oil. The length of the trunk pipelines is more than 225,000 km. Pipeline infrastructure characteristic of oil and gas industry in the Russian Federation is shown in Table 1.

Table 1: Pipeline infrastructure characteristic of oil and gas industry (EMERCOM of Russia, 2017)

Pipeline type	Object length ($\times 10^3$ km)		Wear degree (%)			
			Basic production assets		Protection systems	
	2015	2016	2015	2016	2015	2016
In the Russian Federation						
Trunk gas-pipeline	7,036.20	9,694.61	28.30	28.66	20.76	18.49
Trunk oil-pipeline	6,301.96	5,855.96	32.24	31.76	20.55	20.58
Oil product pipeline	450.59	159.62	20.02	20.52	9.94	10.14
Field pipeline	11,437.39	11,467.89	27.37	26.85	10.32	927
In the Siberian Federal District						
Trunk gas-pipeline	3.771	3.771	49.8	50.3	25	25
Trunk oil-pipeline	6.32	6.32	51	52	25.6	25.6
Oil product pipeline	3.09	3.09	26.5	27	18	18
Field pipeline	0.87	0.87	65	66	15	15

The average number of pipeline failures in 1999 – 2009 (per 1,000 km of Russian trunk pipelines) amounted to 0.06/y, there were 0.32/y refusals for West European pipelines during the same period, in North American pipelines – 0.48 (Mokrousov, 2015). The main causes of accidents with Russian trunk pipelines during 2005 – 2015 were: corrosion of the metal pipe – 48 %, defects of the construction (manufacturing) – 22 %, mechanical impact – 15 %, design defects (defective product) – 8 %, personnel incorrect actions in the operation – 6 %, equipment wear – 1 % (Kislitsin and Machnev, 2017).

The initial stage of pipe corrosion failure is connected with corrosion spots occur (Maruschak, Prentkovskis and Bishchak 2016). After a while the spots merge together forming a common spot along the axis of the pipeline. At the next stage a critical destruction of the pipeline walls and hole formation occurs and the pipeline contents leak. If a corrosive area without leakage or an already appeared small leakage is not detected, it will lead to a serious accident – a rupture of the pipeline.

Without denying the importance of the above factors, it is impossible not to mention the fact that most of the oil and gas producing and transportation companies in Western Siberia work in the areas with high bogs (more than 20 %) and a dense hydrographic network. Its function in initially difficult conditions that contribute to the rapid equipment wear and deviations from design requirements due to periodic flooding, high humidity of soils, not provided deformations process of water channels, shores of lakes, uneven freezing and thawing of soils and so on (Ivanova et al., 2014).

In Tomsk region, there are more than 143 underwater crossings of pipelines through water objects with a total length of pipelines of almost 11,000 km including three trunk oil pipelines. The potentially dangerous areas are the crossing of oil pipelines with a large number of streams, small and large rivers, ravines and other gutters creates the danger of rapid oil spillage into large rivers including Ob, Vasyugan, Parabel, Chaya, Shudelka, and Ilyak causing significant environmental damage.

Currently, organisations that calculate the risks of an accident on underwater oil pipeline crossings use the Eq(1), in which only underwater crossing distance is used and the tabulated value of the leakage frequency from process pipelines (Table 2).

$$P = L \cdot Y \quad (1)$$

Where:
P – probability, y^{-1};
L – underwater crossing distance, m;

Y – leakage frequency from process pipelines, $m^{-1}\cdot y^{-1}$.

Table 2: Leakage frequency from process pipelines *(EMERCOM of Russian Federation, 2009)*

Pipeline diameter (mm)	Leakage frequency ($m^{-1}\cdot y^{-1}$)				
	Small (12.5 mm)	Medium (25 mm)	Large (50 mm)	Very large (100 mm)	Rupture
900	$3.1\cdot 10^{-7}$	$1.3\cdot 10^{-7}$	$5.2\cdot 10^{-8}$	$2.2\cdot 10^{-8}$	$4.2\cdot 10^{-9}$
1,200	$2.4\cdot 10^{-7}$	$9.8\cdot 10^{-8}$	$3.9\cdot 10^{-8}$	$1.7\cdot 10^{-8}$	$3.2\cdot 10^{-9}$

Oil discharge and environmental damage assessment in the calculation emergency situations scenarios for typical underwater crossings of trunk oil pipelines for the Ob basin (Tomsk region) was carried out in accordance with the procedural recommendations (RD 03-496-02, 2002). As the examples of such emergency cases are considered for the following:

1) Development of the most dangerous emergency scenario when there is a rupture of the pipeline with the entire volume discharge of pumped oil through this pipeline section (between valves), the scenario probability is $5\cdot 10^{-6}$ y^{-1};

2) Development of the most likely emergency scenario when a damage occurs such as a formation of a crack or a hole in the pipeline wall with the discharge of only a part of the pumped oil volume through this pipeline section (between valves), the scenario probability is $6\cdot 10^{-4}$ y^{-1}. Table 3 shows the comparison of oil discharge amount in the most dangerous and most likely scenarios.

Table 3: Comparison of oil discharge volume in the most dangerous and most likely scenarios for typical underwater trunk oil pipeline crossings for the Ob River basin

Characteristic parameters of an underwater trunk oil pipeline crossing	Oil discharge volume (t)	
	The most dangerous scenario	The most likely scenario
1. D 1,220 mm, river bed width 100 m, length of pipeline section 3 km;	7,000	600
2. D 1,020 mm, river bed width 800 m, length of pipeline section 4.5 km;	6,000	500
3. D 1,220 mm, river bed width 50 m, length of pipeline section 4 km;	2,000	700
4. D 1,220 mm, river bed width 80 m, length of pipeline section 4.5 km;	3,000	70
5. D 1,020 mm, river bed width 120 m, length of pipeline section 3.7 km.	10,000	80

3. Leak prevention and detection

Current monitoring systems for pipelines, such as acoustic system, parametric system, vibroacoustic monitoring, and insulating coating of a pipeline monitoring system, provide large leaks detection and have a sensitivity limit about 1 % of pipeline capacity. Low-intensity leaks (less than 1 % of pipeline capacity) are not detected by such systems.

Periodic visual inspection of oil pipelines helps to identify the presence of leakage signs of oil and oil products but it is ineffective in places of underwater crossings. Oil pipeline that crosses water bodies is laid under the bed or along the bottom of a water body. In winter, oil pipeline inspection is complicated by the fact that the majority of water bodies are under ice in Russia. The applied air patrolling and aerospace surveying provide data on the observed leaks only when they reach a significant scale. These methods require verifying on the ground and additional time for images decoding.

3.1 Screening approach

The use of screening control is proposed to prevent and promptly detect the occurrence of leaks in oil pipelines in water body crossing places. Screening method is aimed at rapid detection of pollution source. The monitoring of cases connected with exceeding the background value of a controlled parameter in an environmental object is the basis of the screening method.

Available experience of applying screening approach for the detection of oil pollution in water bodies has shown that screening has a high potential for detecting leaks of oil and oil products in oil pipelines in water body crossing places (Adam et al., 2016). For this purpose, the most significant screening criteria were identified taking into the estimation oil and gas complex impact on the surface water resources of the region. It is suggested to use direct (oil products containing by fluorescence response) and indirect indicators specific conduction as screening criteria at the same time.

Placement of screening sensors: It is proposed to choose the placement of screening sensors on for detecting leaks in oil pipelines in water body crossing places on the following key control sites of the water body:

1) Relative background areas of water bodies upstream from the supposed source;

2) The distance from potential sources (downstream) is not more than 500 m.

The key sites for screening sensors location are selected depending on the characteristics of a water body and an oil pipeline.

3.2 Experimental part

Oil is a multicomponent mixture with the complex composition of hydrocarbons. The formation of an analytical signal in the fluorescent method occurs due to aromatic structures. The polyaromatic hydrocarbons (PAHs) fluoresce upon excitation in the visible and near-UV spectral range, the proportion of PAHs depends significantly on the oil product nature, their content in crude oil varies between 5 % and 55 %. The UV-fluorescent method has a high sensitivity. Therefore, identification of oil contamination in a water body can be determined promptly on the presence of an aromatic component, even in case of its minimum content.

To model oil pollution in water, oil-water solutions were used with the range of oil concentrations from the maximum permissible concentration (MPC) to saturated (oil-water ratio 1:1). For this purpose, several oil samples (from light to heavy) of the West Siberian oil and gas province were used. The excitation spectral region of 255 – 400 nm was used in the study of samples. However, the excitation spectral region 340 – 360 nm was selected for further use in the screening study.

The choice of excitation spectral region 340 – 360 nm is associated with several reasons. The change in the analytical signal intensity from the excitation spectral region has the weakest dependence in this range. Furthermore, the emission spectrum remains practically unchanged in this region compared to the spectrum at the excitation wavelength of 260 nm, as shown in Figures 1 - 3). Another reason, the cost of developing a screening UV-sensor in the excitation spectral region 360 – 365 nm is more accessible than 260 – 280 nm.

Figure 1 shows the fluorescence spectra of oil-water solutions (Meretoyahskoe oil field) at the excitation wavelength of 260 nm.

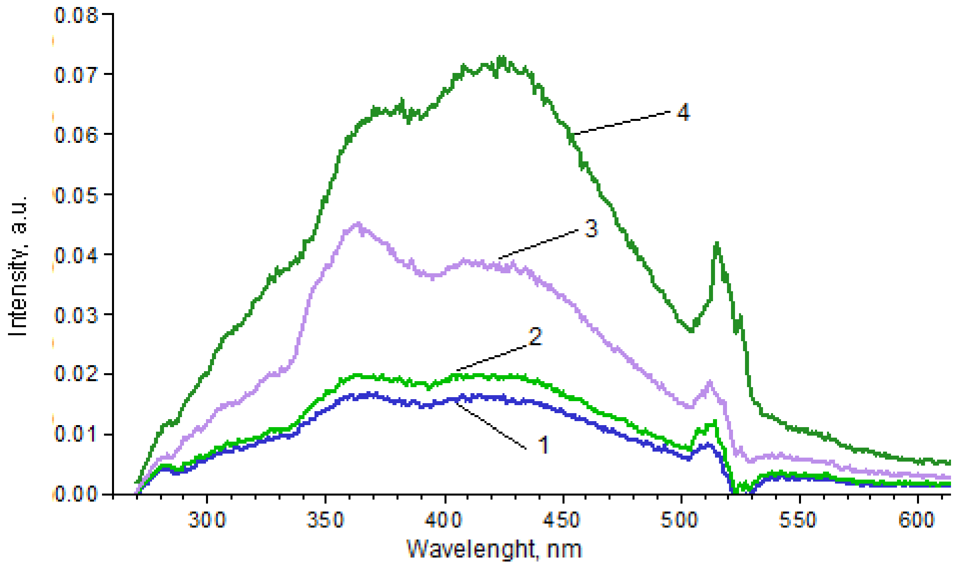

Figure 1: Fluorescence spectrum of the oil in water solution (Meretoyahskoe oil field), excitation wavelength – 260 nm where dilution ratio of the saturated oil in water solution corresponds to: 1 – 10-fold, 2 – 8-fold, 3 – 4-fold, 4 – 2-fold.

Figure 2 shows the fluorescence spectra of oil-water solutions (Meretoyahskoe oil field) at the excitation wavelength of 360 nm. Obviously, the spectra contours of the samples which excited at 260 and 360 nm are different, but the fluorescence spectra contours do not change at 360 nm. This means that they are less dependent on the concentration of oil in water.

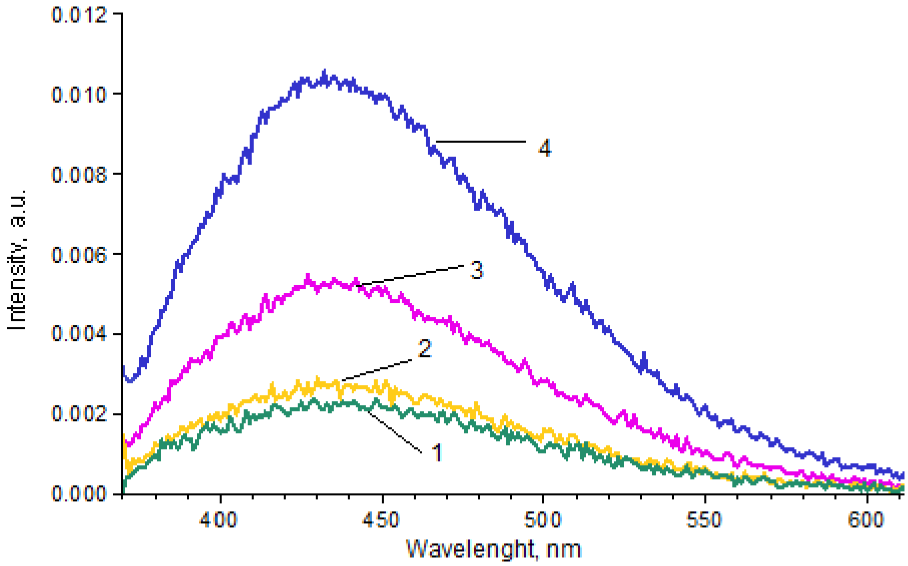

Figure 2: Fluorescence spectrum of the oil in water solution (Meretoyahskoe oil field), excitation wavelength – 360 nm where dilution ratio of the saturated oil in water solution corresponds to: 1 – 10-fold, 2 – 8-fold, 3 – 4-fold, 4 – 2-fold.

4. Results and discussion

The modelling of oil pollution based on laboratory and real water samples has revealed that oil in contact with water formed stable dispersion "oil-water" system which allows a confident identification of pollution only by the fluorescent response from aromatic fraction presence.

The sensitivity of the fluorescent method and also the manufactured sensor give response at the concentration lower by MPC (fishery standard 0.005 mg/L). It is determined that the most intense response of the analytical signal is observed at the excitation spectral region of 260 – 280 nm, but it is highly dependent on the oil composition in this field. For further screening studies, the operating excitation spectral region of the UV-source is 340 – 360 nm. The excitation samples in this spectral region can reduce the dependence of the analytical signal from the oil composition. It was revealed that the chloride ion concentration of more than 50 mg/L would give indirect confirmation of oil contamination.

One of the interfering factors of the fluorescent determination of oil contamination in natural waters is the presence of dissolved organic matter. They are found in each and every type of natural water. Humic substances comprise up to 50 % of the dissolved organic matter in natural waters. Humic substances absorb UV-light well and luminesce in the UV and visible spectral range, namely in the same analytical signal region as oil and oil products.

In this case, the screening approach involves periodically checking the background fluorescence response at the sites of water bodies upstream of the underwater oil pipeline crossing. The leak identification will be detected comparing the analytical signal before and after the underwater oil pipeline crossing.

Because of the high quantity of bogs on the Tomsk region territory, the high content of humic substances is peculiar for the rivers in the amount of up to 0.1 – 0.2 mg/L. They enter aquatic environment because of decomposition of water vegetation remains and peat formation (Adam et. al., 2016). Therefore, more confident identification of anthropogenic oil pollution would be possible with the concentration of dissolved and emulsified oil in water of more than 1 mg/L and at the distance from the potential source by not more than 500 m at the initial leak stage (before an accident).

5. Conclusions

When calculating the potential oil discharge volume in the environmental damage the effective preventive measures application such as screening control of the state of water bodies in places of underwater oil pipeline crossings become obvious. It should be pointed out that early leak detection by the screening control system reduces the rupture probability by at least one order of magnitude.

The screening control system installation only for large and medium-sized water bodies will have a payback period of up to 2 y. This assessment is made in comparison with an environmental damage value of the accident according to the most likely scenario for the region.

Therefore, the detection of oil products content excess by screening control will allow revealing a leak at an early stage of its occurrence. This process enables to reduce oil pollution release scale and minimize environmental damage. The screening systems applying with remote data transmission systems at the same time will be particularly relevant for remote and hard-to-reach regions, where the use of conventional leak detection methods is costly.

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