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IMPACT OF NON-ISOTHERMAL OIL PIPELINES ON THE ENVIRONMENT

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With the development of the network of main oil pipelines, there is a continuous increase in the level of technical support of pipelines, improvement of technological processes of oil pumping. One of the methods of transporting highly viscous and congealing oil is pumping with heating. Today, this is one of the most reliable and easy-to-maintain ways of transporting such oil. During the operation of such pipelines, a significant temperature difference occurs at their initial section, which has a negative impact on the environment. The impact of pipeline transport of oil and oil products on the environment is specific: in case of failure of the linear part of the pipeline, almost all components of the environment are more or less exposed to harmful effects.

The aim of the work is to reduce the impact of non-isothermal oil pipelines on the environment by predicting the environmental risk. The object of research is non-isothermal oil pipelines. To predict the environmental risk, a mathematical model of the movement of oil, which takes into account the effect of temperature on the distribution of pressure in the pipeline, has been improved. To assess the impact of non-isothermal oil pipelines on the environment, the amount of oil that will flow out of the defective hole in the event of an emergency is determined. At the same time, the main factor is the pressure above the center of the defective hole, which is found taking into account the oil temperature. The overall heat transfer coefficient is determined according to the dependence proposed by the author.

The influence of oil temperature on the environment during the operation of the oil pipeline was studied. It was established that during the operation of non-isothermal oil pipelines, a significant temperature drop is observed in their initial section, which has a negative impact on the environment. The methodical basis of predictive assessment of relative environmental risk is proposed, which allows comparing the real value of the risk with its maximum permissible value. *Key words:* pressure, temperature, environmental risk, mathematical model, pipeline.

Вплив неізотермічних нафтопроводів на довкілля. Кривенко Г.М.

З розвитком мережі магістральних нафтопроводів відбувається безперервне підвищення рівня технічного забезпечення трубопроводів, удосконалення технологічних процесів перекачування нафти. Одним із способів транспортування високов'язкої і застигаючої нафти є перекачування з підігрівом. Сьогодні це один з найбільш надійних і простих в обслуговуванні способів транспортування такої нафти. При експлуатації таких трубопроводів на їх початковій ділянці виникає значний перепад температур, що негативно впливає на навколишнє середовище. Вплив трубопровідного транспорту нафти і нафтопродуктів на навколишнє середовище є специфічним: у разі виходу з ладу лінійної частини трубопроводу практично всі компоненти навколишнього середовища більшою чи меншою мірою піддаються шкідливому впливу.

Метою роботи є зменшення впливу неізотермічних нафтопроводів на навколишнє середовище шляхом прогнозування екологічного ризику. Об'єктом дослідження є неізотермічні нафтопроводи. Для прогнозування екологічного ризику удосконалено математичну модель руху нафти, яка враховує вплив температури на розподіл тиску в трубопроводі. Для оцінювання впливу неізотермічних нафтопроводів на навколишнє середовище визначено, яка кількість нафти буде витікати з дефектного отвору у результаті виникнення аварійної ситуації. При цьому основним чинником є тиск над центром дефектного отвору, який знайдено з урахуванням температури нафти. Загальний коефіцієнт тепловіддачі визначено за запропонованою автором залежністю.

Досліджено вплив температури нафти на навколишнє середовище під час експлуатації нафтопроводу. Встановлено, що під час експлуатації неізотермічних нафтопроводів на початковій їх ділянці спостерігається значний перепад температур, що шкодить довкіллю. Запропоновано методичні основи прогнозної оцінки відносного екологічного ризику, що дозволяють порівняти реальне значення ризику з його гранично допустимим значенням. *Ключові слова:* тиск, температура, екологічний ризик, математична модель, трубопровід.

Formulation of the problem. One of the methods of transporting highly viscous and congealing oil is pumping with heating. Today, it is considered the most reliable and easy-to-maintain method of transporting highly viscous and congealing oil. The viscous liquid is heated in heat exchangers or heat furnaces before being pumped into the pipeline. As it moves through the pipeline, it cools down. It should be noted that during the operation of isothermal pipelines, the oil temperature will also change during operation. The impact of pipeline transport of oil and petroleum products on the environment is specific. After all, in case of failure of the linear part of the pipeline, almost all components of the environment are exposed to harmful effects to a greater or lesser extent. Failures of main oil pipelines caused by man-made, natural, and anthropogenic factors disrupt the natural regime of soils and water bodies and pollute the atmosphere, which often leads to environmental disasters.

The relevance of the research and the connection of the author's work with important scientific and practical tasks. The most dangerous environmental pollution occurs in accidents of main oil pipelines, especially large diameters. Accidents pollute a large area, and oil, seeping into the soil, affects its physical and chemical properties. In some cases, in the event of accidents, the oil directly enters the reservoirs. Groundwater can also be polluted. When the spilled oil evaporates, the atmosphere is polluted with volatile hydrocarbons. Oil pipelines, as well as pressurized facilities, are subject to increased reliability requirements, as accidents, in addition to imminent danger to service personnel, pose a risk of environmental pollution. In the process of designing and operating the oil transportation system, its impact on the environment is insufficiently taken into account and the risk is not enough assessed and analyzed. Ensuring safety is mainly limited to maintaining certain distances between the route of the main pipelines and infrastructure facilities. It should be noted that pipeline transport is inextricably linked with the implementation of a set of environmental measures on a fundamentally new scientific and technical basis for the design, construction, and operation of main oil pipelines. Therefore, the problem of researching factors influencing environmental risk during the operation of non-isothermal pipelines is relevant. During the long-term operation of such pipelines, emergencies occur, which can lead to oil leakage from defective holes in the body of the pipe and environmental pollution. Analysis of the consequences of emergency situations during the operation of non-isothermal oil pipelines will make it possible to take the necessary measures to prevent the occurrence of emergency situations in a timely manner. This is the practical significance of the author's work.

Analysis of recent research and publications. The reasons for pipeline failures are covered in many works, in particular, by [1, 2, 3]. Forecasting and assessment of oil losses during the emergency situation are given in the articles [4, 5]. The works of [6, 7] are devoted to research in the field of oil pumping and the influence of various factors on thermal and hydraulic regimes. However, the relationship between thermal and hydraulic conditions and its effect on the nature of the pressure distribution along the pipeline were not taken into account when forecasting oil losses due to damage to the linear part of the pipeline. This is especially true for pumping high-viscosity oil [8].

Highlighting previously unresolved parts of the general problem, to which the specified article is devoted. From the analysis of literature sources it follows that when determining the pressure distribution on a non-isothermal pipeline, it is necessary to consider the thermal and hydraulic processes in the relationship, which will more accurately predict possible oil leaks in the event of an emergency during the operation.

The aim and objectives of the study. The aim of the work is to reduce the impact of non-isothermal oil pipelines on the environment by forecasting environmental risk. To achieve this goal, the following research objectives were formulated: consider the thermal and hydraulic process in conjunction to predict possible oil leaks in the event of an emergency; investigate the impact of oil temperature on the environment during the operation of the pipeline; carry out a forecast assessment of environmental risk.

The subject of study: oil pipeline.

Research methods: mathematical modeling of the studied processes was used during the research.

Novelty and general scientific significance. The novelty of this study lies in the comprehensive analysis of thermal and hydraulic processes during oil pumping through a pipeline. The results, combined with other research, will enable a more precise determination of potential threats during emergency situations on oil pipelines, which will make it possible to develop measures to prevent the occurrence of harmful effects on the environment.

Presentation of the main material. When considering mathematical models of processes in a pipeline system, it should be noted that the thermal and hydraulic modes are interrelated. Building a mathematical model of the motion of high-viscosity oil in a pipeline means formulating a closed system of equations that describes the laws of its dynamics. The stationary non-isothermal flow of oil in the main oil pipeline can be described using a system of equations that includes the continuity equation, equation of motion, and energy balance equation [9]. After performing some mathematical transformations, we obtain a system of differential Eqs. (1, 2) that considers both thermal and hydraulic calculations together

$$\frac{dp}{dx}=\frac{(K\pi d(t-t_0))\dfrac{\partial\Phi_1}{\partial t}+\Phi_2\dfrac{\partial\Phi_3}{\partial t}}{\dfrac{\partial\Phi_1}{\partial t}\cdot\dfrac{\partial\Phi_3}{\partial p}-(1+\dfrac{\partial\Phi_1}{\partial p})\dfrac{\partial\Phi_3}{\partial t}}\ , \tag{1}$$

$$\frac{dt}{dx}=\frac{\Phi_2\cdot\dfrac{\partial\Phi_3}{\partial p}+(K\pi d(t-t_0))\dfrac{\partial\Phi_1}{\partial p}}{(1+\dfrac{\partial\Phi_1}{\partial p})\cdot\dfrac{\partial\Phi_3}{\partial t}-\dfrac{\partial\Phi_1}{\partial t}\cdot\dfrac{\partial\Phi_3}{\partial p}}. \tag{2}$$

We introduce the following functions

$$\Phi_1=\frac{M^2}{S^2\rho},\ \Phi_2=\frac{\Delta_r\lambda M^2}{2d\rho S^2}+\rho g\sin\alpha\ ,\ \Phi_3=MI\ , \tag{3}$$

where M – mass flow rate, kg/s; p – pressure, Pa; d – internal diameter of the pipeline, m; S – cross-sectional area, m^2; λ –friction factor; ρ – the density of oil, kg/m^3; g – the gravitational acceleration, g = 9.81 m/s^2; K – the total heat transfer coefficient from oil to the environment, W/(m^2·K); x – longitudinal coordinate, m; I – the specific enthalpy, m^2/s^2; t – oil temperature, ^{0}C; t_0 – ambient temperature, ^{0}C; Δ_r – mean velocity, m/s; Δ_r – correction for non-isothermal flow, Δ_r = 1.05; α – the angle of inclination of the pipeline to the horizontal. The correction for non-isothermal flow takes into account the dissipation of mechanical energy.

The novelty of the proposed mathematical model is that the heat transfer coefficient from the oil moving in the pipeline to the environment is proposed to be determined taking into account the difference in oil temperatures according to the method described in [1].

$$K = 6.315656 - \frac{33.7669}{\Delta T}, \quad (4)$$

where ΔT – temperature difference.

During the transportation of high-viscosity oil, a laminar flow or turbulent flow in hydraulically smooth pipes is observed. The friction factor does not depend on the roughness. The friction factor in the laminar flow is determined by the Stokes formula. The formula given by Haaland [10] is used to determine the friction factor in turbulent flow.

$$\frac{1}{\sqrt{\lambda}} = -1.8\lg\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon / d}{3.7}\right)^{1.11}\right], \quad (5)$$

where *Re* – Reynolds number; *d* – internal diameter of the pipeline, m; ε / d – relative roughness.

The enthalpy of oil *I*, viscosity ν and density ρ depending on temperature and pressure are found by the known equations given in [11].

Should be consider how the pressure and temperature of the oil will change along the pipeline, using the Eqs. (1, 2). Initial data: At the beginning of the pipeline pressure $P_1 = 3.9$ MPa, pressure at the end of the pipeline $p_2 = 0.15$ MPa, mean velocity 1.25 m/s, $t_1 = 50\ {}^0$C – the temperature at the beginning of the pipeline, the temperature at the end of the pipeline $t_2 = 19\ {}^0$C; $t_0 = 5\ {}^0$C – ambient (soil) temperature, diameter $d = 0.250$ m, pipeline length 50 km, oil density $\rho_{20} = 845$ kg/m^3, kinematic viscosity $\nu_{20} = 18 \cdot 10^{-6}$ m^2/s, $\nu_{60} = 2.8 \cdot 10^{-6}$ m^2/s.

Based on the results of the calculations, we build graphs of pressure and temperature distribution along the length of the pipeline (Fig. 1, 2).

From the analysis of Fig. 1, which shows the nature of the pressure distribution along the pipeline, it follows that the pressures determined by the proposed Eq. (1) and without taking into account the thermal regime and dissipation of mechanical energy differ, which must be taken into account when forecasting oil leakage situations.

The movement of real fluid is always accompanied by energy loss, even when flowing through a smooth-walled pipeline. The main cause of such losses is the

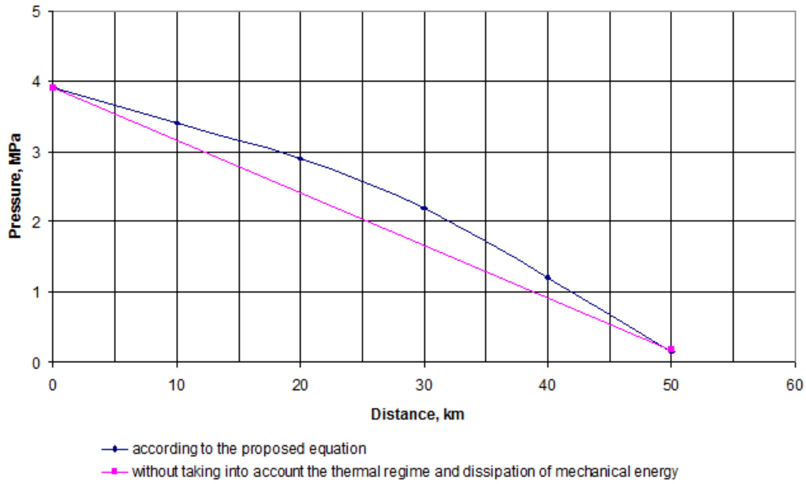

Fig. 1. Pressure distribution along the pipeline

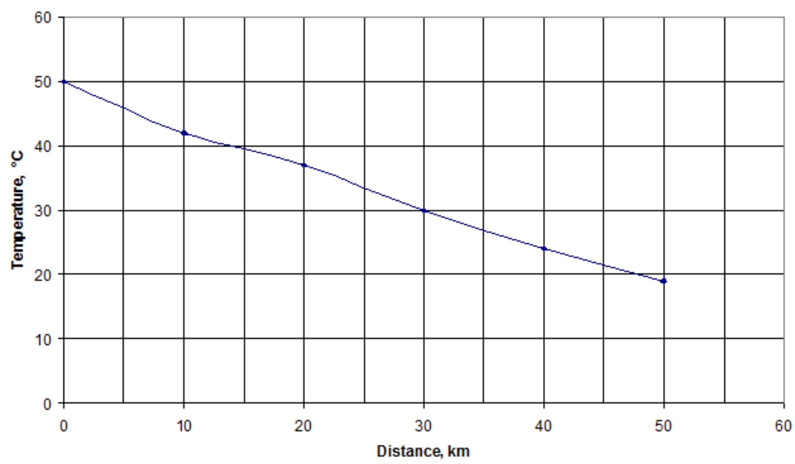

Fig. 2. Temperature distribution along the pipeline

internal friction of the fluid due to its viscosity. Therefore, when pumping high-viscosity oil, the effect of viscosity on the amount of head loss is quite significant. Thus, the pressure loss will be greater and the pressure at the end of the pipeline will be lower. To reduce the impact of non-isothermal pipelines on the environment, it is necessary to predict the amount of oil that may leak from a defective hole during an emergency. The pressure over the center of the defective hole, which is found according to Fig. 1, is one of the main factors affecting the amount of oil leakage. Given the nature of the oil pressure distribution along the pipeline and the presence of defects in the pipe body according to the diagnostic results, it is possible to predict how much oil will flow out of the defective hole as a result of an emergency.

Volume flow rate

$$Q = \mu s\sqrt{2g\Delta H} = \mu_f s\sqrt{2\frac{p_{in} - p_{out}}{\rho}}, \qquad (6)$$

where μ – the discharge coefficient; s – the cross-sectional area of the orifice, m^2; g – the gravitational acceleration, m/s^2; ΔH – the head difference, m; p_{in} – the pressure inside of the pipe, Pa; p_{out} – the pressure outside, which depends on the environment where the oil flows, Pa; ρ – the density of oil, kg/m^3; μ_f – the discharge coefficient, which takes into account the filtration property of the soil.

Therefore, the amount of oil in units m^3 that was spilled from the emergency orifice over time τ, will be $V=Q\cdot\tau$. Here τ = 2.5 hours [1] (from the moment of depressurization of the pipeline to the moment of identification of an emergency situation and shutdown of the pump station). Heated oil poses a special danger to the environment in the event of an accident at the beginning of the pipeline, which must be taken into account when operating a non-isothermal pipeline.

The nature of the temperature distribution, determined by Eq. (2), makes it possible to identify the most dangerous areas relative to the temperature difference. For example, for the pipeline under study, the temperature difference at the depth of laying the pipeline varies on average from 50 ˚C to 19 ˚C, a section up to 30 km from the beginning of the pipeline is dangerous (Fig. 2). Let's calculate the heat release into the environment for the investigated pipeline according to the method given in [11], (Fig. 3). For underground oil pipelines, the environment is the soil at the depth of pipeline laying. The distribution of heat release in the environment corresponds to the change in temperature in the dangerous area up to 30 km from the beginning of the pipeline and in the area from 30 km to 50 km. From the analysis of Fig.3 it follows that there is a significant heat release along the pipeline, which affects the environment, especially in the initial section of the pipeline. The total heat release into the environment is 2563 kJ/s. As Ukraine is permeated by a network of oil and gas pipelines with a total length of up to 40 thousand km, during their operation there is substantive thermal pollution of the environment.

The higher the initial heating temperature of highly viscous solidifying oil, the more damage is done to the environment. For example, in the winter, a melting zone will inevitably appear around the pipeline, resulting in the formation of new drainage strips along the pipeline, and the removal of soil. The use of thermal insulation only slows down these processes. The thermal effect of the pipeline on the environment lasts throughout the life of the structure. It follows that the operation of main oil pipelines is impossible without the requirements of environmental protection.

Particular attention should be paid to the trouble-free operation of non-isothermal oil pipelines. The magnitude of the environmental risk in the operation of main oil pipelines depends on the probability of an accident. Since the quantitative assessment of the level of environmental

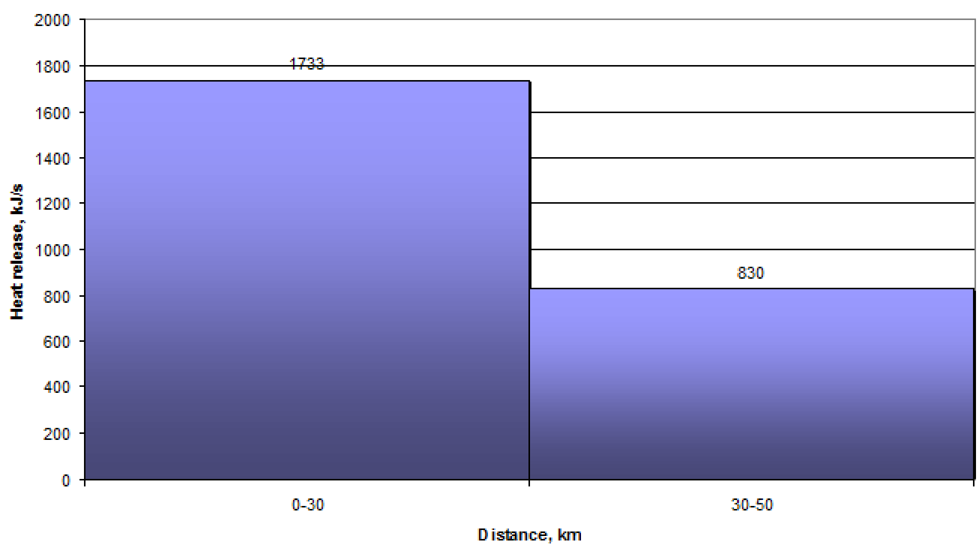

Fig. 3. Distribution of heat to the environment along the pipeline

risk does not allow us to resolve the question of its acceptability or unacceptability, the concept of relative environmental risk R_r is introduced, which allows comparing the real value of the risk acceptable environmental risk R_{en} with its maximum allowable value $R_{en.max}$. The average failure rate on main oil pipelines is taken for calculations.

The relative environmental risk is determined by the following equation

$$R_r = \frac{R_{en}}{R_{en.\max}} = \frac{\varphi}{\varphi_m} \cdot \sum_{i=1}^{n} \frac{V_i}{V_{\max} \cdot n} \cdot \sum_{i=1}^{n} \frac{s_i}{s_{\max} \cdot n}, \qquad (7)$$

where φ– failure rate, 1/ (year· km); φ_m – the average failure rate on main oil pipelines, which according to [1], is 0.36 year^{-1} per 1000 km; n – the number of defects in the body of the pipe (according to the results of diagnosis); V_i – the predicted volume of oil that may leak from the defective orifice, m^3; V_{max} – the maximum allowable volume of oil at the time of leakage; S_i – the area of pollution at the volume of V_i; S_{max} – the maximum allowable area of contamination.

The area of the oil slick formed during this period of time at the outflow increases both with the increase of the outgoing oil temperature (at a constant soil temperature) and the soil temperature (at a constant oil temperature) and with the increase of the oil outflow value at a constant oil temperature). Dependence between spot area S (м^2) and leakage value V(м^3) [12]:

$$S = 53{,}5V^{0{,}89}. \qquad (8)$$

Calculations by formula (10) show that the environmental risk for the pipeline section is R_r=0,052. If the maximum relative environmental risk to take $R_{r\ \max}$= 1, then the investigated section of the pipeline can be attributed to the environmentally friendly.

Conclusions. To predict environmental risk, the mathematical model of oil movement has been improved, which considers the influence of the thermal regime on the pressure distribution in the pipeline. The improvement of the method of thermohydraulic calculation consists of the proposed mathematical model for determining the full heat transfer coefficient depending on the temperature difference of oil, taking into account the dissipation of mechanical energy, as well as the simplicity of its implementation.

During the operation of non-isothermal oil pipelines in their initial section, there is a significant temperature difference, which has a negative impact on the environment. Heat release into the environment for the investigated pipeline in the initial section with a temperature difference of 30 ^{0}C is 2 times more than in the area with a temperature difference of 11 ^{0}C.

Predictive assessment of relative environmental risk allows comparing the real value of risk with its maximum allowable value. The environmental risk for the section of the investigated pipeline is R_r=0,052.

Prospects for the use of research results. The results of scientific research presented in this article can serve as a basis for forecasting the environmental risk during the operation of non-isothermal oil pipelines. Further research involves predicting hazard risks at oil and gas industry facilities.

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