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TECHNOLOGICAL AND ENERGY ADVANTAGES OF INDUCTION HEATING IN OIL TRANSPORTATION SYSTEMS BY PIPELINES

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ТЕХНОЛОГІЧНІ ТА ЕНЕРГЕТИЧНІ ПЕРЕВАГИ ІНДУКЦІЙНОГО НАГРІВУ В СИСТЕМАХ ТРАНСПОРТУВАННЯ НАФТИ ТРУБОПРОВОДАМИ

Purpose. To study the potential and effectiveness of induction heating in modern oil pipeline transportation systems in order to identify ways to improve the technical efficiency, operational reliability, and environmental sustainability of the infrastructure through the implementation of innovative energy-saving technologies.

The methods. Numerical methods were applied taking into account the nonlinear temperature dependence of oil viscosity and the processes of formation and accumulation of paraffin deposits. The main task of modeling is to ensure the optimal heating mode with minimal energy consumption. Analysis of the example confirmed that the oil temperature $T_f(z)$ increases along the pipeline from 20 °C to 80-100 °C, depending on the thermal load, insulation quality and length of the section.

Findings. The results obtained demonstrate the effectiveness of induction heating for reducing operating costs, improving the hydraulic regime, increasing throughput and reducing the risk of man-made accidents. The calculated pressure drop ($\Delta P \approx 2.62$ kPa) corresponds to the permissible operating conditions of main systems and does not create a critical load on the pumping equipment. At the same time, the temperature $T_f(z)$ stably exceeds the critical value of paraffin crystallization (T_c = 30 °C), which indicates the effectiveness of the implemented heating mode at a heat flux q = 1000 W/m^2.

The originality. The study proposes an improved approach to mathematical modeling of induction heating, taking into account the complex relationships between heat flows, hydrodynamic characteristics, and changes in the physicochemical properties of oil. Particular attention is paid to establishing the relationship between temperature and viscosity and the rate of paraffin formation. The innovative nature of the technology as a high-tech and energy-efficient solution for modernizing oil transportation infrastructure is emphasized.

Practical implementation. The proposed technology facilitates the modernization of energy infrastructure and the development of digital solutions for managing oil transportation systems. Maintaining a temperature of $T_f(z) \geq T_c$ in all considered scenarios ensures continuous transportation of paraffin-saturated oil without deposit formation, reducing energy costs and the risk of accidents.

Keywords: *induction heating, oil transportation, pipelines, energy efficiency, mathematical modeling, viscosity, paraffin deposits, environmental safety, modernization, digitalization.*

Introduction. Oil transportation via pipelines is a critical and integral part of the oil industry, which plays a key role in ensuring energy security of both individual states and the global economy as a whole. This infrastructure is a fundamental element of the energy chain, ensuring a stable and uninterrupted supply of oil, the main raw material for the production of fuel, chemical products, building materials and other industries. At the global level, pipeline transport forms the basis of the modern energy system, ensuring a balance between the production, processing and consumption of energy resources [1, 2].

Compared with other modes of transportation, in particular road, rail and sea, pipeline oil transportation is characterized by high economic efficiency and technical reliability. growing global demand for energy resources, as well as in cases where it is necessary to ensure uninterrupted supply to territories with diverse geographic and climatic conditions [3, 4].

Separately, it is worth noting the significant advantages of pipeline transport from the standpoint of safety and environmental friendliness [5]. negative impact on ecosystems. This aspect is becoming especially relevant in the context of strengthening international environmental standards and the global trend towards sustainable development [6].

In addition, the development of the pipeline network has a significant impact on the geopolitical stability and economic development of regions [7, 8]. socio-economic development [9].

At the same time, the efficiency and stability of pipeline systems are largely determined by the physicochemical properties of the transported oil, which can vary significantly depending on the geological origin, chemical composition, temperature conditions and impurity content [10]. Viscosity is a key parameter determining the hydrodynamic resistance to flow; its growth leads to an increase in energy costs for the operation of pumping equipment, which, in turn, leads to an increase in operating costs and accelerated wear of technical equipment [11]. threatening to stop the technological process and the occurrence of emergency situations [12].

This problem becomes especially acute in low temperature conditions typical for northern regions, such as Canada and Alaska, where the ambient temperature can drop significantly below zero [13, 14].

Given the above, in order to ensure efficient and uninterrupted transportation of oil, it is necessary to implement innovative technological solutions that allow maintaining optimal temperature conditions and reducing the viscosity of the product. in the metal walls of the pipeline, which leads to their local and rapid heating. As a result, heat is transferred directly to the oil, which helps to improve its flow properties and reduce viscosity [15, 16].

The main part. Induction heating has a number of significant advantages over traditional temperature support methods, such as steam or electric heating using heating elements [17]. In particular, this technology is highly energy efficient, since thermal energy is generated directly in the pipe metal, which minimizes heat loss to the environment [18]. In addition, induction heating provides fast and accurate regulation of the heating level, uniform temperature distribution along the pipeline, and reduces the risk of local overheating or damage to materials [19]. Environmental safety is another significant advantage of induction heating. Since this method does not involve the use of open flame, heating liquids or other potentially hazardous heat carriers, it helps to reduce the likelihood of accidents, leaks and environmental pollution. This is especially important in the context of strengthening international environmental standards and the desire of the oil industry to reduce the negative impact on the environment. Increasing the viscosity of oil at low temperatures is one of the most pressing, complex and common technical problems arising in the process of transporting petroleum products through pipeline systems. Viscosity as a physical characteristic of a liquid determines the internal friction between its layers and reflects the degree of "thickness" or resistance to fluidity of the medium. An increase in viscosity has a significant impact on the mobility of oil in pipelines, since increased viscosity is accompanied by an increase in hydraulic resistance to flow, which makes it difficult to ensure uninterrupted and effective circulation. A decrease in temperature, typical for regions with a cold climate, as well as characteristic of underground and offshore pipelines, leads to a significant increase in oil viscosity. This physical process is associated with a decrease in the kinetic energy of molecules, which leads to a slowdown in their interaction and limits the mobility of the liquid [20, 21]. An increase in viscosity leads to an increase in hydraulic resistance, which leads to the need to increase the operating pressure in pumping systems to maintain the specified flow parameters. As a result, energy costs increase, in particular an increase in electricity consumption by pumping equipment, as well as accelerated mechanical wear of its components. Increased equipment load is accompanied by increased capital and operating costs for maintaining stable operation of oil transportation systems, and also increases the risk of emergency situations caused by overloads of pumping units. This problem is especially acute when working with heavy oil fractions, which have a more complex molecular composition and high density. Increased viscosity of these fractions leads not only to an increase in the load on the pumping equipment, but also contributes to the acceleration of its operational wear as a result of increased friction and pressure. This, in turn, increases the likelihood of technical malfunctions, which negatively affects the continuity of operation, causes downtime, accidents and disruptions in the supply of petroleum products. In addition, high viscosity causes uneven movement of oil in pipes, contributes to the emergence of turbulence zones, hydrodynamic instabilities and the formation of stagnant zones, which reduces the efficiency of the system and complicates its monitoring and management.

Formation of paraffin and asphaltene deposits is one of the most common and dangerous consequences of oil cooling during transportation through pipelines. Paraffins are high-molecular hydrocarbons that, when the temperature decreases, transform into a crystalline solid state, settling on the inner surface of pipes and forming persistent deposits that significantly narrow the flow area. A similar process is observed in the case of asphaltenes – complex organic compounds with a high molecular weight that can form dense polymer structures. The accumulation of such deposits leads to a significant decrease in the diameter of pipes, an increase in hydraulic resistance, a deterioration in throughput and potential blockage of the flow. This creates serious technical and economic problems, increasing energy costs and the risk of accidents, such as depressurization and rupture of the pipeline, threatening the safety of personnel and the environment.

To eliminate and prevent the formation of deposits, regular and technologically complex pipe cleaning operations are carried out, including mechanical, chemical and thermal methods, which significantly increases operating costs. Energy costs for maintaining the temperature regime during oil transportation make up a significant share of the total costs of delivering petroleum products. To reduce viscosity and prevent the formation of paraffin and asphaltene deposits, various methods of heating the pipeline system are widely used to maintain oil in a temperature range that ensures optimal flow conditions and stability of the transport process. Traditional heating methods include the use of open fire, steam boilers, electric heating elements and circulation of hot coolants. However, each of these methods has significant drawbacks: low energy efficiency, significant heat losses, increased fire hazard, high capital investments, high energy consumption and uneven heat distribution. The latter leads to local overheating or insufficient heating, which can cause damage to pipeline materials and the formation of stagnant zones. Given this, there is an urgent need to develop and implement the latest heating technologies that would provide effective, safe and energy-saving control of the temperature regime during oil transportation. One of the promising areas is the use of induction heating based on the phenomenon of electromagnetic induction. This method allows local and uniform heating of metal pipelines directly in the pumping zone, which helps to reduce energy costs, increase operational safety and minimize the negative impact on the environment. Induction heating is considered one of the most promising methods of thermal action on structural materials, based on the use of a fundamental physical phenomenon - electromagnetic induction. According to the provisions of electrodynamics, when a conductive material interacts with an alternating magnetic field, eddy currents (Foucault currents) are induced in its structure, circulating in closed circuits. As a result of the passage of these currents through a material with a certain specific electrical resistance, electromagnetic energy is converted into thermal energy, which leads to a local increase in temperature within the field's action zone.

In practice, the source of the alternating magnetic field is an inductor - an electromagnetic coil connected to a high-frequency alternating current generator. In pipeline transport systems, inductors can be placed externally or built into the pipeline structure in order to bring the magnetic field as close as possible to the metal shell of the pipe. During induction heating, energy is transferred directly to the pipe walls made of an electrically conductive metal, resulting in their heating. Subsequent heat transfer to the liquid medium – oil – is carried out by thermal conductivity through the inner surface of the pipeline. In the context of oil transportation infrastructure, induction heating is a technologically feasible solution for regulating the temperature regime during oil transportation. This is especially important given that a decrease in the temperature of the raw material leads to an increase in its dynamic viscosity, deterioration of rheological characteristics, a decrease in fluidity and the formation of crystalline phase inclusions in the form of paraffins and asphaltenes. These phenomena entail an increase in hydraulic resistance, an additional load on the pumping equipment and the formation of deposits on the inner walls of the pipeline, which reduces the efficiency and reliability of the system as a whole.

Increasing the temperature of the oil flow by induction heating helps to reduce the viscosity of the raw material, improve its transport properties and reduce flow resistance. This in turn allows to optimize the operation of pumping units, reduce specific energy costs for pumping and stabilize the hydrodynamic parameters of the flow. In addition, reducing the likelihood of stagnant zones and reducing the intensity of paraffin and asphaltene deposition has a positive effect on the operational reliability of the pipeline.

Induction heating has a number of significant advantages over traditional methods of temperature control, among which are steam generation, electric heating elements or circulation of liquid coolants. One of the key technical advantages is the possibility of localized, dosed and uniform heating of individual sections of the pipeline that suffer the greatest heat loss or are prone to deposit formation. Due to this, the overall energy efficiency of the system is increased, operating costs are reduced and the service life of the equipment is extended.

Induction heating also demonstrates advantages from the standpoint of technogenic and environmental safety. Its operation does not involve the use of open flame or flammable liquids, which reduces the risk of emergency situations associated with fires or explosions. The absence of the need for external heat carriers reduces the likelihood of leaks and complications during maintenance. In addition, the simplicity of the induction system design facilitates its integration into automated control and diagnostic systems. In the context of the actualization of global challenges related to sustainable development, energy transformation and environmental responsibility of industrial facilities, induction heating is gaining additional weight. Its implementation is not accompanied by emissions of combustion products into the atmosphere, which allows to significantly reduce the carbon footprint of oil transportation enterprises and ensure compliance with international environmental standards.

The use of induction heating in technological processes of pipeline transportation of oil is considered as one of the key areas of modernization of the industry. its feasibility and strategic importance from the standpoint of engineering and operational, economic and environmental analysis.

One of the key technical advantages of induction heating is the ability to purposefully increase the temperature of the oil product, which leads to a significant reduction in its dynamic viscosity. equipment, optimize pumping modes and reduce the duration of the transport cycle.

The problem of paraffin formation and agglomeration of asphaltenes, which occurs due to a decrease in the temperature of crude oil during transportation, deserves special attention. solid phase, reduce the risk of pipe clogging and extend the service life of pipeline infrastructure and auxiliary equipment.

Induction systems are characterized by a high degree of spatial controllability, which allows for the implementation of a localized thermal load on individual sections of the pipeline. This is especially important for segments with increased heat losses, as well as areas with an increased risk of stagnation. which significantly increases the overall efficiency of the pipeline thermal subsystem. From a safety point of view, induction heating demonstrates significant advantages over traditional methods of heat supply. systems. These characteristics are extremely important when operating pipelines in difficult or remote regions, in particular on the shelves, in marine areas or industrial areas with an increased level of man-made risk.

The environmental safety of induction heating is another key argument in favor of its widespread implementation. Since induction heating does not involve combustion processes, it is not accompanied by emissions of harmful substances such as carbon dioxide, nitrogen oxides, sulfur or products of incomplete combustion of fuel. This allows to significantly reduce the carbon footprint of transport infrastructure operation, ensure compliance with modern environmental standards and contribute to the implementation of national and international decarbonization strategies. Induction heating also organically integrates into the green energy paradigm, which enhances the environmental responsibility of the oil and gas industry. Modern induction units are characterized by a high degree of automation and the ability to integrate with digital process control platforms, including SCADA systems. This ensures operational monitoring and regulation of temperature conditions in real time, allows to take into account changes in the physicochemical parameters of the transported oil, adapt to external climatic factors or changes in the system load. Thus, induction heating can be considered as a key element of the "smart pipeline" concept, focused on the digital transformation of infrastructure [22, 23].

In addition, unlike traditional heating technologies, induction systems are characterized by a short response time – the heating activation process begins almost instantly after the electric current is supplied. This ensures the dynamic flexibility of the system, allows it to quickly adapt to changes in the process mode, as well as quickly respond to emergency situations without the need for lengthy preheating.

Induction heating demonstrates high efficiency even under difficult operation, in particular in underground, underwater, arctic or other hard-to-reach sections of the pipeline. Due to their compactness, tightness and resistance to aggressive environments, induction systems are able to function stably at high humidity, pressure drops or low temperatures.

It is also important to note the adaptive potential of induction units, which can be designed taking into account the material of the pipeline (in particular, carbon, alloy or stainless steel), its geometric parameters, wall thicknesses and route configuration. This enables individual design and optimization for different types of transport systems – from long-distance main pipelines to distribution or intra-industrial networks.

Within the adaptive potential of induction units, we will consider an example of modeling an induction heating system for transporting oil through a pipeline. To do this, it is necessary to formulate the initial parameters of the system and assumptions: a cylindrical pipe with an internal radius r_i, an external radius r_0, and a length L; an induction coil generates heat q (W/m^2) on the outer surface of the pipe; oil flows at a rate of Q (m^3/s) and has the following thermophysical properties: density ρ, heat capacity c_p, thermal conductivity k_f, viscosity $\mu(T)$, which depend on temperature; paraffin crystallizes at a temperature below T_c (crystallization temperature); oil temperature at the inlet T_{in}, external temperature of the environment T_{ext}; heat losses to the environment are taken into account due to the heat transfer coefficient h; the oil flow is laminar or turbulent, depending on the Reynolds number. Taking into account all the above initial parameters of the system and assumptions for correct modeling, it is necessary to solve the heat balance equation for $T_f(z)$ numerically, taking into account the dependence of h_f on Re and $\mu(T)$ and determine the minimum power of the coil q, so that for all z.

Heat balance equation for oil, where the oil temperature $T_f(z)$ along the pipe changes due to heat exchange with the pipe wall [24, 25]:

$$\rho Q c_p \frac{dT_f}{dz} = 2\pi r_i h_f \left(T_w - T_f\right), \tag{1}$$

where $T_f(z)$ is the temperature of the inner pipe wall; h_f is the heat transfer coefficient between oil and the wall.

Heat transferred from an induction coil through a pipe wall. Heat conduction equation in a cylindrical wall (steady state):

$$\frac{1}{r}\frac{d}{dr}\left(r k_m \frac{dT_m}{dr}\right) h_f = 0, \tag{2}$$

where $T_m(r)$ is the temperature in the pipe wall, k_m is the thermal conductivity of the metal; limiting conditions on the outer surface ($r = r_0$); limiting conditions on the inner surface ($r = r_i$).

In turn, the solution to this equation gives the temperature distribution in the wall:

$$T_m(r) = T_w + \frac{q r_0}{k_m} \ln\left(\frac{r}{r_i}\right). \tag{3}$$

The viscosity of oil depends on temperature and is determined by:

$$\mu(T) = \mu_0 \exp\left(\frac{E_a}{RT}\right), \tag{4}$$

where μ_0, E_a, R are constants characterizing oil. A decrease in viscosity at higher temperatures facilitates free flow.

The pressure drop in the pipe depends on the viscosity and flow regime.

$$\Delta P = f \frac{L}{2r_i} \frac{\rho v^2}{2}, \tag{5}$$

where v is the average flow velocity, f depends on the Re number.

Taking into account all the above initial parameters of the system and assumptions for solving the model, it is necessary to solve the heat balance equation for $T_f(z)$ numerically, taking into account the dependence of h_f on Re and $\mu(T)$ and determine the minimum coil power q, so that $T_f(z) \geq T_c$ for all z. Let us assume that h_f, μ, c_p are constant. Then the solution of the heat balance equation:

$$T_f(z) = T_{ext} + \left(T_w - T_{ext}\right)\left(1 - \exp\left(-\frac{2\pi r_i h_f z}{\rho Q c_p}\right)\right). \tag{6}$$

The coil power q is selected so that $T_f(L) \geq T_c$ and determine the minimum coil power that ensures the given condition for all $z \in [0, L]$ and the permissible pressure drop $\Delta P \leq \Delta P_{\max}$.

As an example, we will plot a graph of the dependence of oil temperature $T_f(z)$ on distance z (Fig.).

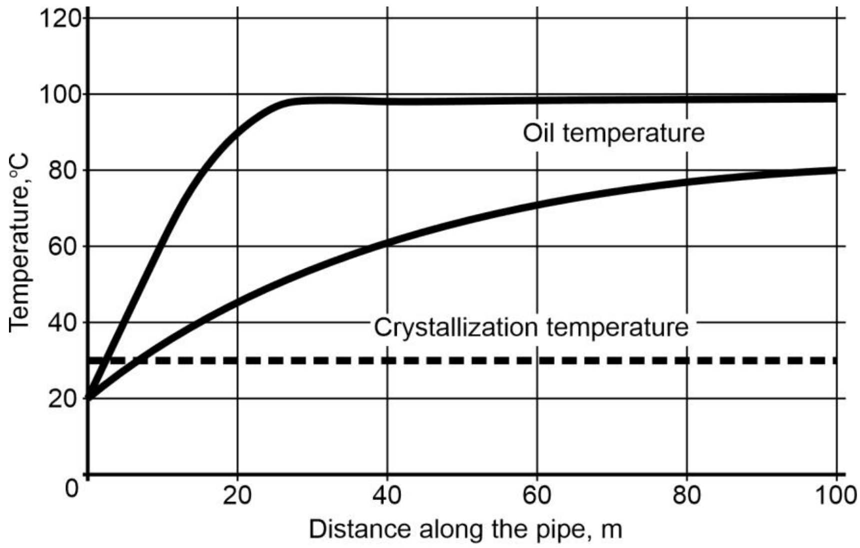

Fig. Graph of oil temperature $T_f(z)$ versus distance z

An analysis of the calculation example shown in Figure allows us to formulate a number of weighty conclusions regarding the efficiency of the temperature control system during oil transportation. In particular, it was found that the oil temperature $T_f(z)$ along the pipeline route gradually increases from the initial value of 20°C to 80–100°C. Such a temperature regime is formed depending on the transportation conditions, in particular, the intensity of the heat load, the characteristics of the thermal insulation coating and the length of the pipeline section.

It is important that in all analyzed conditions the temperature $T_f(z)$ does not decrease below the critical crystallization temperature of paraffin (T_c = 30°C), i.e. the condition $T_f(z) \geq T_c$ is met. This is of key importance for ensuring continuous, reliable and safe transportation of paraffin-saturated oil, since avoiding the phase transition of paraffins prevents the formation of deposits on the inner walls of pipelines. The accumulation of such deposits complicates the hydraulic flow regime and can lead to increased energy costs or emergency situations.

The calculated pressure drop ($P \approx 2.62$ kPa) confirms the acceptability of the hydraulic operating conditions typical for typical main oil transportation systems. This pressure level does not create critical loads on the pumping equipment and does not require a significant increase in energy consumption.

The graphical data presented in Figure indicate that the oil temperature consistently exceeds the critical value along the entire pipeline, which is direct evidence of the efficiency of the implemented heating scheme at a thermal load of $q = 1000$ W/m^2. Consequently, the use of this heating mode is advisable given the maintenance of proper physicochemical characteristics of oil during transportation and the reduction of risks associated with paraffin formation.

Despite a wide range of technological, economic and environmental advantages, the use of induction heating in oil pipeline transportation systems in practice is accompanied by a number of significant challenges. Overcoming them requires a thorough feasibility study, a high level of engineering support and significant capital investments at the initial stage of project implementation. One of the main limiting factors is the high capital cost of implementing induction systems on long sections of pipelines. The main costs are the purchase and installation of powerful alternating current sources, inductors, control systems, highly sensitive temperature sensors, electronic modules and communication equipment. When deploying a system on large or geographically complex sections of a pipeline (in particular in arctic, marine or mountainous conditions), it is also necessary to take into account the costs of logistics, specialized equipment and the involvement of highly qualified personnel. Compared with traditional thermal heating systems, such as steam generators or heat carriers, induction technologies are characterized by significantly higher initial costs. However, in the long term, these investments can be compensated by reducing operating costs, increasing energy efficiency and reducing the frequency of maintenance.

Another important aspect is the need for specialized materials or design solutions that ensure effective interaction of pipeline systems with the induction field. The efficiency of induction heating directly depends on the electromagnetic properties of pipes, in particular electrical conductivity, magnetic permeability and specific electrical resistance. In the case of using pipes made of materials that are not suitable for effective induction heating, it may be necessary to partially replace pipeline segments or to retrofit them with additional elements that facilitate localization and uniformity of heating. Also, in areas with increased heat loss or geometric deviations, compensating modules may be required to equalize the temperature field. All these factors complicate the design and increase the cost of system modernization.

Special attention must be paid to ensuring uniform heat distribution along the entire pipeline. Insufficiently optimized temperature distribution caused by uneven geometry, heterogeneity of the material or local heat losses can lead to the formation of local overheating zones. This is fraught with premature aging of structural materials, damage to sealed joints, disruption of the integrity of the pipeline and an increased risk of emergency situations. To prevent such consequences, the design of an induction system should include detailed computer modeling of thermal processes, calculation of the electromagnetic field, optimization of the shape and placement of inductors, as well as the introduction of intelligent automated control systems that provide dynamic regulation of temperature parameters in real time.

Additionally, it is necessary to take into account the high requirements for a stable and uninterrupted power supply, without which the operation of induction systems is impossible. In regions with underdeveloped energy infrastructure or dependence on diesel generators, providing power supply in the required volume can become a limiting factor. This, in turn, requires additional investment in the development or modernization of power supply systems. Summarizing the above, it can be stated that the existing technical and economic challenges do not neutralize the strategic potential of induction heating, but they determine the need for a systematic, step-by-step and interdisciplinary approach to its implementation. Effective implementation of this technology requires: – a thorough technical and economic analysis at the pre-project preparation stage; involvement of specialists in the field of energy, materials science, automated control systems and heat engineering; use of computer modeling to predict operating parameters; adaptation of design and technological solutions to specific operating conditions of the pipeline system.

Conclusions. Induction heating in oil pipeline transportation systems is a promising technology that can significantly improve the efficiency and safety of the process. It will help reduce energy consumption, minimize technical risks and environmental impacts. In the future, the development of induction heating systems will contribute to the modernization of oil infrastructure and increase the competitiveness of the industry.

The introduction of induction heating in oil pipeline transportation systems opens up broad prospects for increasing the reliability, safety and economic efficiency of the oil infrastructure. The use of this technology will help reduce operating costs, increase pipeline capacity, reduce the risk of man-made accidents and improve environmental performance. In the long term, large-scale use of induction heating can become a key factor in the modernization of the oil industry, contributing to its sustainable development in the context of modern economic challenges and strict environmental requirements.

Induction heating acts as an effective, environmentally friendly and economically feasible technology with high potential for large-scale implementation in the infrastructure of pipeline oil transportation. Its application not only increases the reliability and efficiency of oil pipeline operation, but also creates the basis for further modernization and digitalization of energy management systems at industrial facilities.

The mathematical model takes into account thermal and hydrodynamic processes to ensure heating of oil to a temperature above TS, minimizing the energy consumption of the coil. Practical implementation requires modeling taking into account the nonlinear dependence of viscosity on temperature and possible paraffin deposits on the walls.

Induction heating should be considered as a high-tech tool for modernizing oil transportation infrastructure, the implementation of which requires strategic planning and technical and economic balance.

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АНОТАЦІЯ

Мета. Дослідження потенціалу та ефективності застосування індукційного нагріву в сучасних трубопровідних системах транспортування нафти з метою визначення шляхів підвищення технічної ефективності, експлуатаційної надійності та екологічної сталості інфраструктури шляхом упровадження інноваційних енергозберігаючих технологій.

Методика. Застосовано чисельні методи з урахуванням нелінійної температурної залежності в'язкості нафти та процесів утворення й накопичення парафінових відкладень. Основне завдання моделювання – забезпечити оптимальний режим нагріву з мінімальним енергоспоживанням. Аналіз прикладу підтвердив, що температура нафти $T_f(z)$ зростає вздовж трубопроводу від 20 °C до 80-100 °C, залежно від теплового навантаження, якості ізоляції та довжини ділянки.

Результати. Отримані результати засвідчують ефективність індукційного нагріву для зниження експлуатаційних витрат, покращення гідравлічного режиму, підвищення пропускної здатності та зменшення ризику техногенних аварій. Розрахований перепад тиску ($\Delta P \approx 2{,}62$ кПа) відповідає допустимим умовам експлуатації магістральних систем і не створює критичного навантаження на насосне обладнання. При цьому температура $T_f(z)$ стабільно перевищує критичне значення кристалізації парафіну (T_c = 30 °C), що свідчить про ефективність впровадженого режиму підігріву за теплового потоку q = 1000 Вт/м^2.

Наукова новизна. У дослідженні запропоновано вдосконалений підхід до математичного моделювання індукційного нагріву, який враховує складні взаємозв'язки між тепловими потоками, гідродинамічними характеристиками та змінами фізико-хімічних властивостей нафти. Особливу увагу приділено встановленню залежності впливу температури на в'язкість та інтенсивність парафіноутворення. Акцентовано на інноваційному характері технології як високотехнологічного та енергоефективного рішення для модернізації нафтотранспортної інфраструктури.

Практична значимість. Запропонована технологія, що сприяє оновленню енергетичної інфраструктури та розвитку цифрових рішень в управлінні нафтотранспортними системами. Збереження температури $T_f(z) \geq T_c$ у всіх розглянутих сценаріях забезпечує безперервне транспортування парафінонасиченої нафти без утворення відкладень, що знижує енерговитрати та ризики аварій.

***Ключові слова**: індукційний нагрів, транспортування нафти, трубопроводи, енергоефективність, математичне моделювання, в'язкість, парафінові відкладення, екологічна безпека, модернізація, цифровізація.*

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